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Wright-Patterson Air Force Base, Ohio

NET ENERGY ANALYSIS MODEL FOR THE EVALUATION OF A SOLAR HEATING, VENTILATION AND AIR CONDITIONING SYSTEM

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LSSR 32-77B

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This research develops a feasible net energy analysis model from current net energy theory. The net energy model's purpose is to be utilized as an evaluation tool. Net energy analysis is based on the net energy model. Net energy analysis concerns itself with evaluating any system by its performance and interrelationship with the total environment in which the system operates. The model developed specifically addresses a heating, ventilation and air conditioning (HVAC) system. The net energy model was applied to two types of HVAC systems: one powered with conventional fuel sources and one powered with solar energy utilizing a conventional fuel back-up system. The model provided a realistic representation of both HVAC systems. An analysis was conducted on the two systems using data for a base exchange facility at Randolph AFB. The analysis included the use of three net energy analysis measures: net energy, yield ratio, and investment ratio. The results from the net energy analysis were compared to an economic analysis previously conducted to identify differences between the two evaluation methods.

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NET ENERGY ANALYSIS MODEL FOR THE EVALUATION OF A SOLAR HEATING, VENTILATION AND AIR CONDITIONING SYSTEM

A Thesis

Presented to the Faculty of the School of Systems and Logistics

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Facilities Management

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Chapter 1

PROBLEM STATEMENT

Today, many complex public and private decisions concerning energy system development and energy system use are being made. Such energy decisions have received increased emphasis because of the energy crisis. These energy systems are being evaluated within a turbulent social, economic, environmental, and political framework. The energy decisions are a product of competing goals, values, and interests (13:101). Current decisions concerning energy systems and use have resulted from merely an economic analysis of a multitude of highly unpredictable, divergent variables. Economists frequently treat these variables by transforming all or most of them into dollars (13:101). A growing number of individuals are beginning to question whether economic analysis of energy proposals is adequate to equitably evaluate the array of complex inputs to the decision process.

The concept of net energy analysis reduces the variability of many of the inputs to the decision process by converting them into a relatively stable common denominator (13:101). This denominator is energy, in terms of BTUs[1]

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[1]BTU (British Thermal Unit), a convenient measure of energy, is the amount of heat required to raise the temperature of 1 pound of water 1°F.

(British Thermal Units) or kilocalories. Including net energy analysis considerations in the decision process may provide a more complete basis upon which to initiate sound energy decisions. However, no working model depicting an alternative energy system has been formulated from the theory of net energy analysis to evaluate energy system alternatives.

BACKGROUND

The era of low cost clean energy sources is almost dead (22:5). The successful utilization of energy to date has been an essential component of man's ability to survive and develop socially (22:1). It is time, though, to take a hard look at our nation's prodigal use of energy and its pervasive role in our society (4:28). Two factors which dictate the utilization of energy are: (1) available resources and (2) the technology to convert the resources to useful heat and work (7:3). The fact that our fossil fuels are finite was always known, but we believed them to be nearly inexhaustable. We have been rudely awakened to the fact that not only are the reserves of fossil fuels (oil, coal, natural gas) finite but also that the end of easily obtainable fossil fuels is approaching rapidly in the foreseeable future.

The cause for alarm is the phenomenal growth in the rate of consumption of these fossil fuels both here in the

United States and in the world since WW II (22:4). Cheap energy has shaped our postwar society. The most characteristic energy statistic about the United States is that with 6% of the world's population, the U.S. consumes 33% of the world's total energy output (22:1). The U.S. is a prodigious consumer of energy in all forms. In 1973 it consumed 6.3 billion barrels of oil, 600 million tons of coal, and 22.2 trillion cubic feet of natural gas (22:4). This total is approximately 74.7×10^{15} BTU (22:8). If the world maintained its current annual per capita consumption rates, we would be assured of adequate supplies of energy for hundreds of years. However, if worldwide per capita consumption rates were equivalent to those of the U.S. in 1972, the world energy demand would be satisfied for only a few decades at best (15:6-1).

The relationship between reserves and consumption shows the finiteness of the available fossil fuels. Estimates of fossil fuel reserves show an energy content ranging from a low of 113,100 quad* BTU to a high of 295,800 quad BTU, as seen in Table 1 (15:6-1). The estimated cumulative consumption total (fossil and non-fossil) from 1970 to 2030 is from 39,200 quad to 67,000 quad BTU. The projected world total demand (fossil and non-fossil) for the year 2030 is 1,000 to 2,700 quad BTU (15:6-2).

---

*Quad is a short hand term for quadrillion (1.0×10^{15}) or 1,000,000,000,000,000 expressed numerically.

TABLE 1

POSSIBLE RANGE IN MAGNITUDE AND ENERGY CONTENT OF THE WORLD'S SUPPLY OF FOSSIL FUELS (15:6-2)

	Quantity		Energy Content	
	Low	High	Low	High
Coal and Lignite	4000×10^{9} tons	10000×10^{9} tons	88×10^{18} BTU	220×10^{18} BTU
Petroleum	2000×10^{9} bbl	5000×10^{9} bbl	11.6×10^{18} BTU	29×10^{18} BTU
Natural Gas	6000×10^{12} ft^{3}	12000×10^{12} ft^{3}	6×10^{18} BTU	12×10^{18} BTU
Tar-Sands Oil	300×10^{9} bbl	1000×10^{9} bbl	1.7×10^{18} BTU	5.8×10^{18} BTU
Shale Oil	1000×10^{9} bbl	5000×10^{9} bbl	5.8×10^{18} BTU	29×10^{18} BTU
			113.1×10^{18} BTU	295.8×10^{18} BTU

Over the past generation, U.S. consumption of energy increased by an average of 3.2% per year. Growth quickened to a rate of 4.3% annually in the 1960-68 period, and in the late 196[illegible] the total U.S. energy demand seemed to be growing at [illegible] to 5% (22:4). It should also be noted that the [illegible]mand of the world as well as that of the U.S. is expected to increase substantially in the future. These trends and projections on energy demand are presented in Tables 2 through 5.

The way we use our energy today has to be looked at closely, too. To understand why this is an important topic we need to go back to basic thermodynamics. The First Law of Thermodynamics tells us that no matter or energy can be created or destroyed; just changed in form. The Second Law of Thermodynamics states that something is destroyed--not the energy or matter itself, but the <u>usability</u> of it (16:29). Emphasis has been placed by the Second Law of Thermodynamics to suggest a new criterion of efficiency--one that asks not only how well an energy source performs a given function, but whether that source should be used to perform that function at all (16:29). Decision-makers need to examine the functions performed by non-renewable energy sources and to determine those functions that can be performed by renewable energy sources. This policy will free the non-renewable energy sources to perform only their most critical functions.

TABLE 2

PROJECTED RANGES OF WORLD ENERGY DEMAND (15:2-8)
(10^{15} BTU)

	1980	2000	2030
United States	92-113	138- 223	154- 404
World Total	330-420	650-1060	1060-2700

TABLE 3

PROJECTED RANGES OF PER CAPITA
WORLD ENERGY DEMAND (15:2-10)
(10^6 BTU)

	1980	2000	2030
United States	415-490	550-745	560-950
World Total	70- 90	110-165	130-280

TABLE 4

PROJECTED RANGES OF THE ANNUAL GROWTH IN PER CAPITA DEMAND (15:2-14) (Percentage)

	1960-1968	1960-1980	1980-2000	2000-2030
United States	2.8	2.6-3.4	1.3-2.1	0.2-0.9
World Total	3.5	3.0-4.3	2.3-3.1	0.6-1.8

TABLE 5

PROJECTED RANGES OF CUMULATIVE ENERGY DEMAND OVER VARIOUS PERIODS (15:2-15) (10^{18} BTU)

	1970-1980	1980-2000	2000-2030	1970-2030
United States	0.78-0.9	2.3- 3.2	4.4- 9.0	7.5-13.1
World Total	2.6 -2.9	9.2-13.5	27.4-50.6	39.2-67.0

A case in point is the use of fossil fuels for supplying residential and commercial heating in the U.S., as seen in Figure 1 and Figure 2. Approximately *one-fourth of the U.S.* total energy consumption is spent to heat, cool, and supply hot water to homes and places of work (22:10). Yet there exists an alternative energy source (solar energy) whose basic technology and engineering principles have been demonstrated (9:2). The primary barrier is the present relatively high initial investment cost.

Lotka's Principle

It is generally accepted that the basic need of living organic systems is to survive (14:1). Driven by the pervasive evolutionary process, man has attempted to exploit all the resources at his command as well as the free contributions from nature (rain, air, sunshine) in order to maximize his potential for survival (20:90; 14:1). Lotka's principle describes the surviving systems as those "that obtain the largest number of energy sources and that maximize the flow of useful energy through themselves [14:2]."

According to Lotka, then, we should attempt to secure as many energy sources (fossil fuel, natural energy in the form of sunshine, wind, food, rivers, etc.) as we are likely to need (14:2). Possessing these multiple energy sources increases the probability that we will

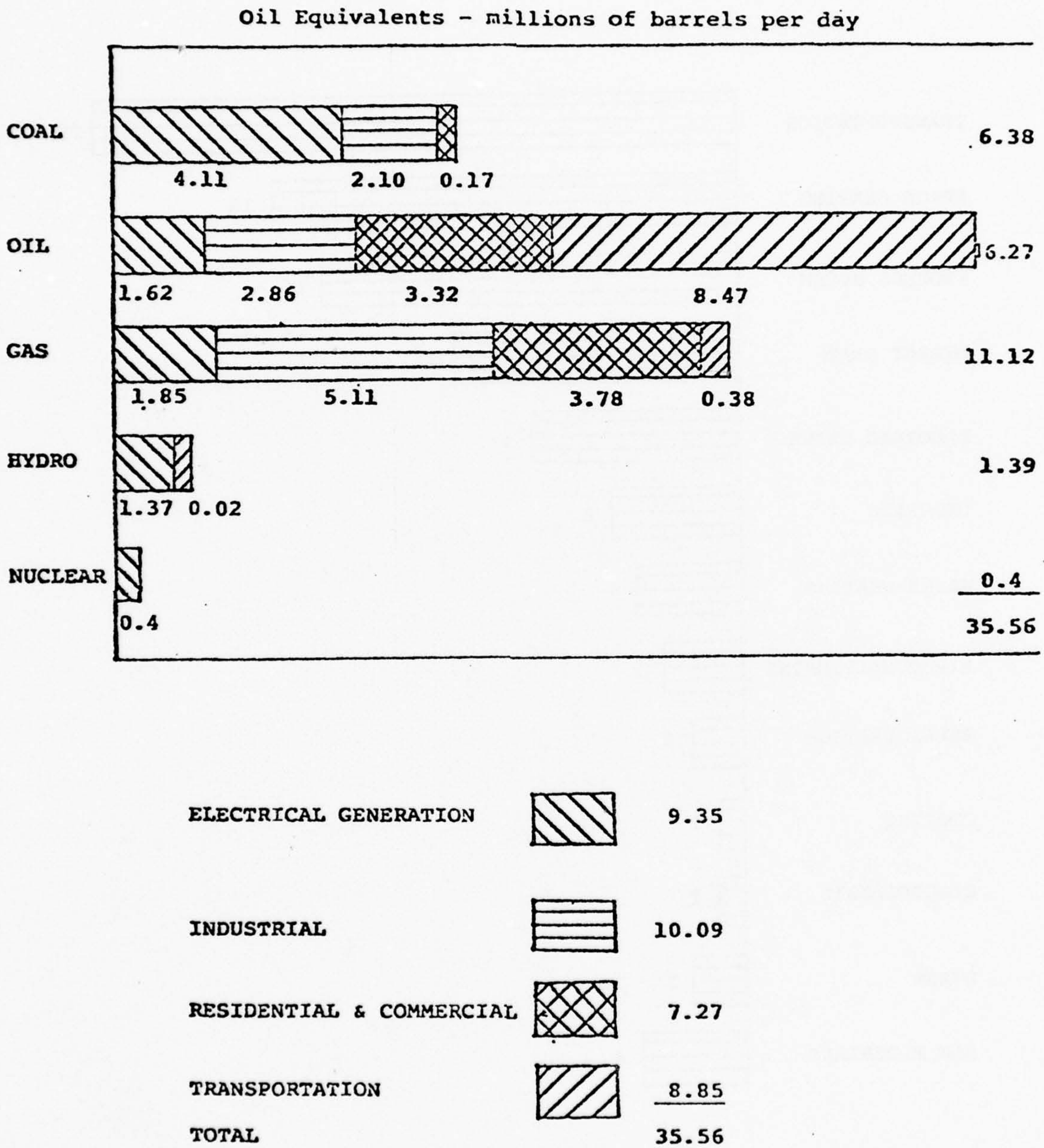

Figure 1

The Pattern of United States Primary Fuel Use (22:9)

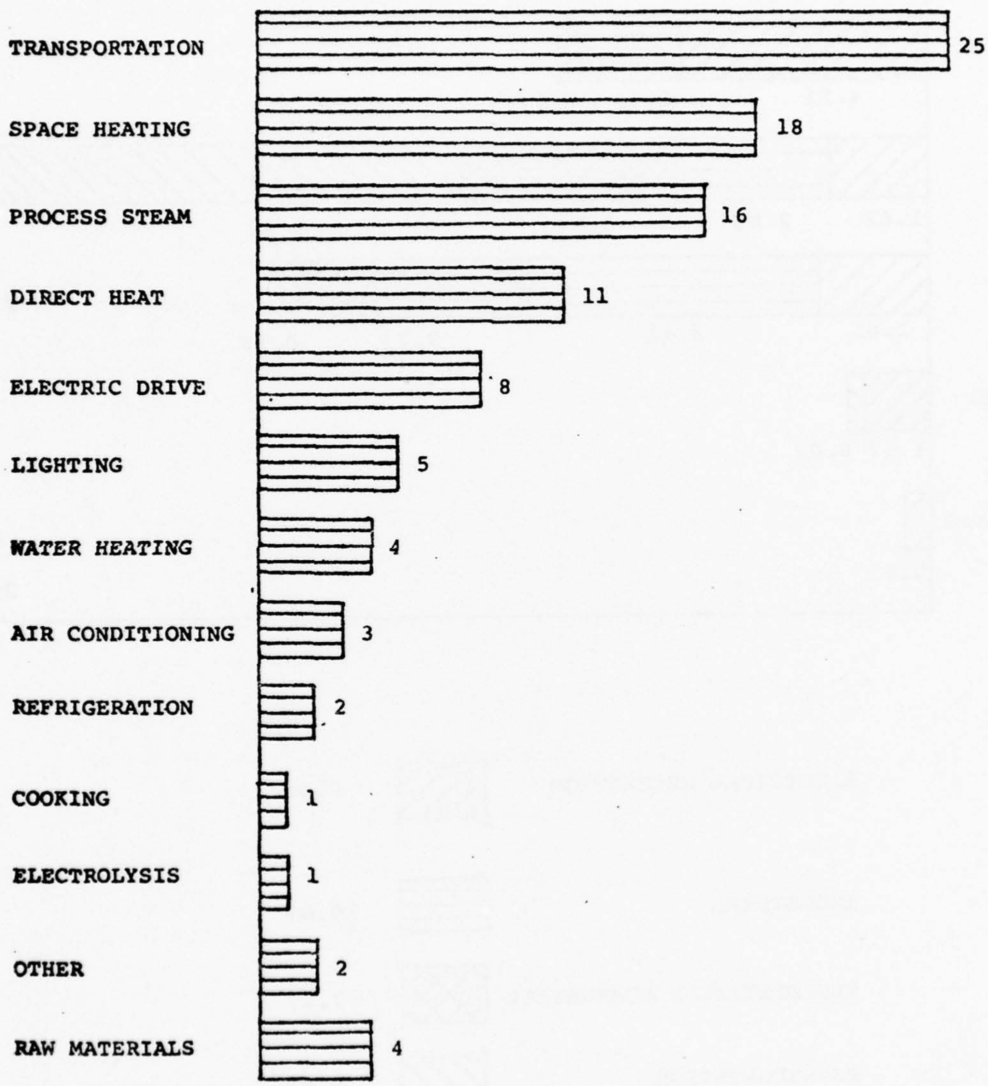

Figure 2

Percentage of United States Energy Use (22:4)

survive. The latter portion of Lotka's principle relates that we must also expend this energy at a rate which permits the greatest amount of useful work per unit time to be performed (14:3). Useful work is defined as activities contributing to survival by improving process efficiency, by creating an output, or by extracting more energy sources. A corollary of Lotka's principle requires that some energy of the system be directed toward generating new possibilities or choices for the system to insure that the system may evolve as the external conditions change.

Systems are also required to store energy to maximize their energy over unexpected interruptions in the flow of energy to or from energy sources (14:4). All the energy flows described by Lotka are subject to the laws of thermodynamics.

Lotka's principle has some important implications for approaching the energy supply/demand dilemma. It dictates that we must expend every effort to discover new sources of energy to insure our continued survival. If energy is in short supply, we must eliminate energy wasteful activities and increase the efficiency of all processes to glean all useful work from the available energy. The transition from an unlimited to a limited energy supply situation can precipitate a traumatic and violent equilibrium process rather than a controlled one which Lotka's principle allows. The importance of Lotka's principle to the decisions

enacted during this transition period is well stated by Jay W. Forrester:

> It is not a question of whether growth will cease, but rather whether the coming transition to equilibrium will occur traumatically or with some measure of human intervention which may head off some of the most tragic outcomes [7:5].

<u>Net Energy Analysis</u>

An interesting "economic" equilibrium concept is that proposed by H. T. Odum. He suggests that money is no longer an adequate medium to describe accurately our various resource allocations and human transactions. Dollar appraisals need to be augmented by a system of energy accounting and simulation to describe how underlying energy/matter exchanges operate and how hidden energy subsidies or outflows obscure or prevent accurate accounting of the real costs, benefits, and trade-offs in human activities. It is no longer a matter of pure economics when considering energy resources. The need is to improve the analysis of inter-relations and trade-offs among environmental consequences, economic costs, material requirements, and resource avail-ability into a comprehensive but simplified set of consis-tent measures drawn from a single, external, conceptual system (7:5). Net energy analysis is the energy accounting system that provides such a mechanism.

Net energy analysis concerns itself with evaluating any system by its performance and interrelationship with

the total environment in which the system operates. Net energy analysis accomplishes this evaluation by stating all inputs, processes and outputs in terms of energy. To make an equitable evaluation of these inputs, outputs, and losses, however, their energy values must be of the same quality. Quality refers to the conversion of one energy form (coal) to another equivalent form (electricity) while acknowledging the energy losses inherent in that conversion process. Net energy analysis takes into account input subsidies to the processes to achieve a given level of output. Subsidies are additional inputs required to maintain a certain level of useful outputs. The objectives of the net energy analysis theory is to determine the net energy of that process system - the sum of the output energies minus the feedback energies (the cost of finding, producing, upgrading and delivering of the energy) equals the net energy in terms of energy equivalents. The greater the net energy of the system, the better are its qualifications for implementation compared to other alternative systems. For example, as we extract more dilute, deeper, remote, and dirtier energy sources, the energy subsidy required to extract and upgrade the new sources increases. Some portion of each year's new energy demand represents additional subsidies to energy extraction (19:220).

Consequently, an increase in energy demand on comsumption may not represent an increase in the amount of net energy

available to do work in the consuming sectors of society. The entire increase could be required to acquire the new energy, but not necessarily, since technological advances may compensate for any decrease in the quality of the resource. Whenever new technological capabilities increase the efficiency of energy extraction, net energy increases. When all the requirements to develop a new energy source or to increase the efficiency of an existing source are determined, it becomes clear that energy limits the ability to obtain these requirements. This leads to the concept of energy as the ultimate limiting factor, which is to say: (1) that energy is the only commodity for which a substitute has not been found, (2) that potential energy is required to run every type of system, and (3) that energy cannot be recycled without violating the Second Law of Thermodynamics (12:1051-52; 11:108)

Since each energy producing effort requires some energy for its development and production, the energy contained in these efforts subsidizes energy production while society receives only the difference or "net" energy (12:1051; 19:220). When considering the various types of energy subsidies, all energy measures must be of the same quality (12:1053). Energy forms are of the same quality if they are equivalent in their ability to do work. Energy quality is determined by evaluating the total energy used in converting from one energy form to another--including the

energy lost during any conversion process and the supplemental energy expended to drive the conversion process. The ratio of the energy produced to the sum of the energy losses and supplemental energy constitute the quality conversion factor (12:1053). For example, a BTU of electricity can do more work than a BTU of coal or oil and, therefore, is of a higher quality because coal and oil suffer higher energy losses in their utilization than electricity. Coal and oil must be burned to transform their chemical energy into usable heat or mechanical energy. This transformation results in thermal and/or frictional losses thereby reducing the original ability of the coal and oil to perform work.

Net energy analysis has captured the attention of individuals searching for better policy analysis tools. Section 5 of the Non-Nuclear Energy Research and Development Act of 1974 states: "The potential for production of net energy by the proposed technology at the stage of commercial application shall be analyzed and considered in evaluating proposals [23:6863]." As a result of this legislation, there are several government agencies trying to develop and standardize net energy analysis procedures for practical evaluation of energy systems. Net energy analysis has the potential to improve the input into the decision-making process. The information and data available to the decision-makers is usually incomplete and conflicting

(12:1053). Energy analysis may not eliminate the incompleteness, but it can reduce the conflicting nature of the inputs. Proving a new energy system logically requires demonstration of engineering feasibility and commercial application. Only after the new energy system satisfactorily demonstrates its capabilities will it attempt to enter into the existing environment (9:2). Finally, whether the new energy source replaces the old and makes a significant contribution depends on simple economics: is it economically competitive? (16:30). Net energy analysis of alternative energy supply technologies can provide more information of a less conflicting nature to the policy and decision-makers to supplement the information in the economic analysis.

Solar Energy

In light of undeniable evidence concerning increasing energy consumption and decreasing fossil fuel energy availability, a search oriented toward developing renewable or essentially inexhaustible alternative energy sources is underway (23:6863). This search has uncovered several feasible energy sources possessing the above characteristics, but none of them are as "ideal" an energy source as solar energy. Solar energy systems generate neither air nor water pollution and only a minimum of thermal pollution by-products (1:41). Besides those highly desirable properties,

there exists no technological barriers to the application of solar systems (21:5). To date, the most practical and real application of a solar energy system is to heat water for household uses and to warm and cool living and work spaces (16:30). Because of the availability and low cost of gas and oil prior to 1974, efforts to use solar energy for heating met with only limited success (9:2). The principal barrier is its present relatively high initial cost (9:2). Solar energy systems for heating water and for space heating and cooling involve a variety of approaches ranging from so-called active systems to passive systems and integration with energy conversion technology. Manufacturers are beginning to market space heating systems, but current acquisition prices are relatively high. The Energy Research and Development Administration (ERDA) believes that solar energy systems are competitive now on a life-cycle basis in new construction of certain heating-only applications (9:2). A typical system for the solar heating and/or cooling of buildings consists of a collector exposed to the sun's radiation, a heat transfer fluid (liquid or air) which carries the converted energy to the points of storage or use, thermal storage devices, cooling or air-conditioning devices and air handling systems for distributing conditioned air within the building spaces (10:III-2). Provisions may be included for domestic hot water, and appropriate pipes, ducts, pumps, fans, heat exchangers and controls as

required. Most systems have an integrated back-up or auxiliary system utilizing conventional fuels (10:III-2). A simple explanation of the system's thermal operation begins with the sun's short wavelength radiation being directed on the surface of a solar collector. The collector is the means by which the short wavelength radiation is converted to long wavelength, thermal grade energy and transferred to a heat transfer medium. The thermal grade energy is then carried to a storage device. This device is a highly insulated tank that accumulates the heat from the medium and minimizes any loss of that heat. The control system activates a pump to circulate the medium when the sun is providing enough solar radiation to heat the medium to a specific level. The auxiliary system is utilized when the solar system reaches a minimum level where it cannot function. This usually occurs when there is a long period in which the solar system cannot capture enough solar radiation because of the weather (6:11; 8:29-31).

In summary, this research will concern itself with the exploration of the integral factors associated with both economic analysis and net energy analysis models and their contributions to the decision-making process effecting the selection of a solar energy system as an alternative energy source. The Preliminary Design Report for the Army Air Force Exchange Service's Base Exchange being

constructed at Randolph AFB, Texas, will supply the researchers with the physical, system, economic and environmental parameters used in the design of that facility (17).

RESEARCH OBJECTIVES

The objectives of this research are to:

1. Evaluate whether the net energy analysis approach lends itself to the development of a practical and feasible model for the analysis of the alternate energy source, solar energy, in a commercial application.

2. Develop a net energy analysis model, if possible, to be used in evaluating the alternate energy source, solar energy, when used in a Heating, Ventilating, and Air Conditioning (HVAC) system.

3. Explain any differences between the economic analysis model used in the Preliminary Design Report and the developed net energy analysis model.

RESEARCH QUESTIONS

Answers to the following research questions will permit achieving the research objectives:

1. Can the theory of net energy analysis be applied to develop a realistic model of a solar assisted HVAC system?

2. What factors are integral to net energy analysis and are integral to model development?

3. Can the model be developed?

4. Is the model a feasible and practical representation of the real system?

5. Can the model be used to evaluate the solar HVAC system?

6. What are the differences between the economic model and the net energy analysis model?

7. What are the advantages and disadvantages of the net energy analysis model as displayed in the evaluation of the solar HVAC system in the Base Exchange at Randolph AFB, Texas?

Chapter 2

METHODOLOGY

This research is concerned with developing a feasible net energy analysis model from available conceptual information and theory. The relevant works of Odum, Berry and Fels, Lem, Kylstra and others have been reviewed to extract the integral factors and major interrelationships of net energy analysis theory. Examination of the basic assumptions incorporated in the net energy anlaysis theory was conducted to identify constraints that may affect practical application and model development.

The researchers constructed a model because the major factors, interrelationships, and constraints can be expressed in forms that are compatible with model development. This model was evaluated to see if it presents a feasible and practical representation of the real system environment. To accomplish this evaluation, all major inputs, processes, and outputs directly affecting the operation of the system were identified.

A major consideration concerning the model was its ability to evaluate the HVAC system. The model was applied to two types of HVAC systems. The two types of systems differ only in their major power sources: (1) conventional

fossil fuel (natural gas and electric) powered HVAC system and (2) thermal solar energy HVAC system with a conventional fossil fuel (natural gas and electric) auxiliary system. In the application of the net energy model to these two systems, the information and results closely resembled the expected information and results. The researchers then determined that the model can be used to evaluate these types of systems.

After obtaining a working model which can be used as an evaluation tool, the researchers proceeded to examine and detail the economic analysis conducted by the design engineers of these two systems in terms of major *factors, relationships and assumptions.* Also, the type and form of the results were analyzed. Finally, the analysis of the economic model and the analysis of the developed net energy analysis model were compared to examine the differences between the two. In this comparison, some of the differences that were looked at include integral theoretical factors, major physical factors, basic assumptions, constraints, and results. The differences are listed along with analysis of the causes for these differences. Finally, total re-evaluation and analysis were conducted to detail the advantages and disadvantages of the use of net energy analysis as an evaluation and decision-making tool.

In conclusion, the researchers proposed some

pro/con recommendations concerning the use of net energy analysis as an evaluation and decision-making tool. Any areas needing improvement and the possible application for its use now and in the future are presented.

<u>Limitations</u>

The limitations of this research are:

1. In developing the model, the researchers only applied it to the evaluation of a HVAC system powered either by solar thermal energy or conventional fossil fuels (natural gas and electricity).

2. The evaluation consisted of only one data set from the Preliminary Design Report for the solar Base Exchange (BX) at Randolph AFB, Texas.

3. Because of the limited time available and only one set of data, the researchers were not able to validate the model externally.

<u>Assumptions</u>

The general assumptions of this research are:

1. The constraints on the model did not affect the capability of the model to be an evaluation and decision-making tool.

2. The application of the model to one set of data established the internal validity of the model.

3. The model can be applied to similar decisions concerning HVAC systems.

Chapter 3

MODEL DEVELOPMENT

In developing a realistic model, one needs to formulate an objective decision-making process that considers the activities of man and the environmental system in which he interacts. It is necessary to know such things as the interactive effects of natural systems, the conversion between dollar and energy flows, and the costs (in terms of energy and dollars) of various activities. Since dollars only flow within man's system, one must switch to another measure that is common to all systems. The exploration, extraction, conversion, transportation, distribution, and even the consumption of materials, goods and services require the use of energy, whether it originates within the natural system or within man's activities.

Energy is used as the common denominator of all systems. The value of energy must accurately reflect the amount of work that can be done by that energy. Therefore, one must adjust energy values to a common quality of energy. This quality of energy conversion will allow one to combine and evaluate the contributions of various systems. Using net energy theory, one can describe any system, in general, as a series of input flows, a process, a series of output

flows, and the losses from conversion processes, the process activity and a possible storage activity. The individual components and flows within the system can be identified and quantified in terms of a single energy value of common quality.

The integral factors in net energy theory are:

(1) The ability to identify flows of energy throughout the system.

(2) The ability to identify the concentrations of energy within the system.

(3) The ability to detail the external inputs (subsidies) which are divided into three types: energy, material, and environmental subsidies.

(4) A conversion between the flow of money and the flow of energy.

(5) A net energy ratio exists and is defined as the ratio of delivered energy yield to the energy value of material, environmental and processed energy subsidies not to include physical and thermodynamic losses directly.

(6) The physical and thermodynamic losses are included only in the sense that increased efficiencies would reduce the losses and increase the delivered energy value.

Scope of Model Development

In developing the model, one should consider several aspects that affect the scope of the model. The

first aspect is that this model will apply only to a heating, ventilation and air conditioning (HVAC) system. The second aspect is the basic model will be applied to both a solar assisted system and a conventional powered system. The third aspect is that the researchers are only concerned with the equipment, facilities and fuel consumption associated with the HVAC system.

The first step in the model development process is to define the system process. The purpose of this HVAC system is to supply heated air, cooled air and hot water to meet the required demands established in the Preliminary Design Report. Next, the identification of the inputs and outputs of the system is accomplished, as shown below.

INPUT FLOWS

- Natural Gas
- Electricity
- Solar Energy
- Water
- Equipment

OUTPUT FLOWS

- Heating Load
- Cooling Load
- Domestic Hot Water (DHW) Demand
- Losses from:
  - Solar Conversion Process
  - Heating Conversion Process
  - Cooling Conversion Process
  - Hot Water Process
  - Storage Tanks

Energy Flow in Model

In developing a model, one needs to show the important internal relationships, the interactions among the subsystems, and the important external energy sources, the driving functions, to help insure that all of the factors are considered that affect the decision. To accomplish this requirement, one can describe the system by diagramming with standard symbols according to laws of energy flow (24: 257). Simplified models in diagrammatic form help visualize where energy flows are large or where they are hidden and often overlooked. Simplified energy analysis models retain the overview and constraints of the total energy flow. Evaluated models facilitate the calculation of the available net energy of sources. The researchers have developed two simple diagrammatic models: the solar assisted HVAC model, Figure 3 and Table 6, and the conventional powered (natural gas/electric) model, Figure 4 and Table 7. These models show the basic energy flows and concentrations within the HVAC system.

Development of Energy Values

Equipment energy values. To support the net energy analysis diagrammatic models previously described, a procedure of transforming the equipment and services used to construct and maintain the system must be developed. Kylstra, of the University of Florida, developed a rudimentary transformation

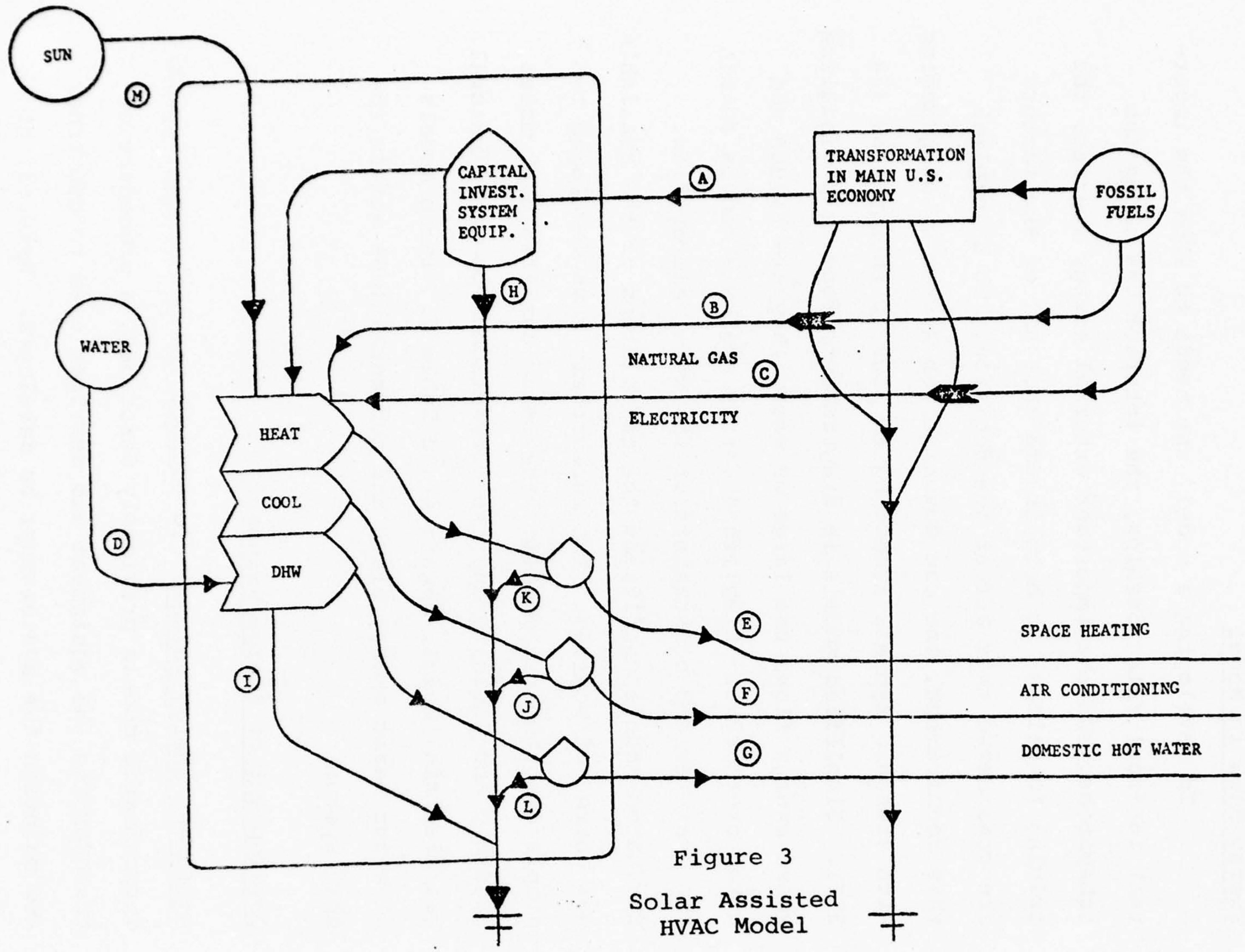

Figure 3

Solar Assisted HVAC Model

TABLE 6

ANNUAL ENERGY FLOWS FOR THE
SOLAR ASSISTED HVAC MODEL

A. Capital Investment Plus Operating Maintenance Cost

B. Fuel Cost for Natural Gas

C. Fuel Cost for Electricity

D. Water Input to System for Domestic Hot Water Use

E. Heat Output Used for Space Heating

F. Cooling Output Used for Space Cooling

G. Domestic Hot Water Output

H. Depreciation of Equipment

I. Losses from the Combined Processes of Heating, Cooling, and Heating Water

J. Loss from any Transfer/Storage of Heated Air

K. Loss from any Transfer/Storage of Cooled Air

L. Loss from any Transfer/Storage of Heated Water

M. Solar Energy Collected in Collector Plates

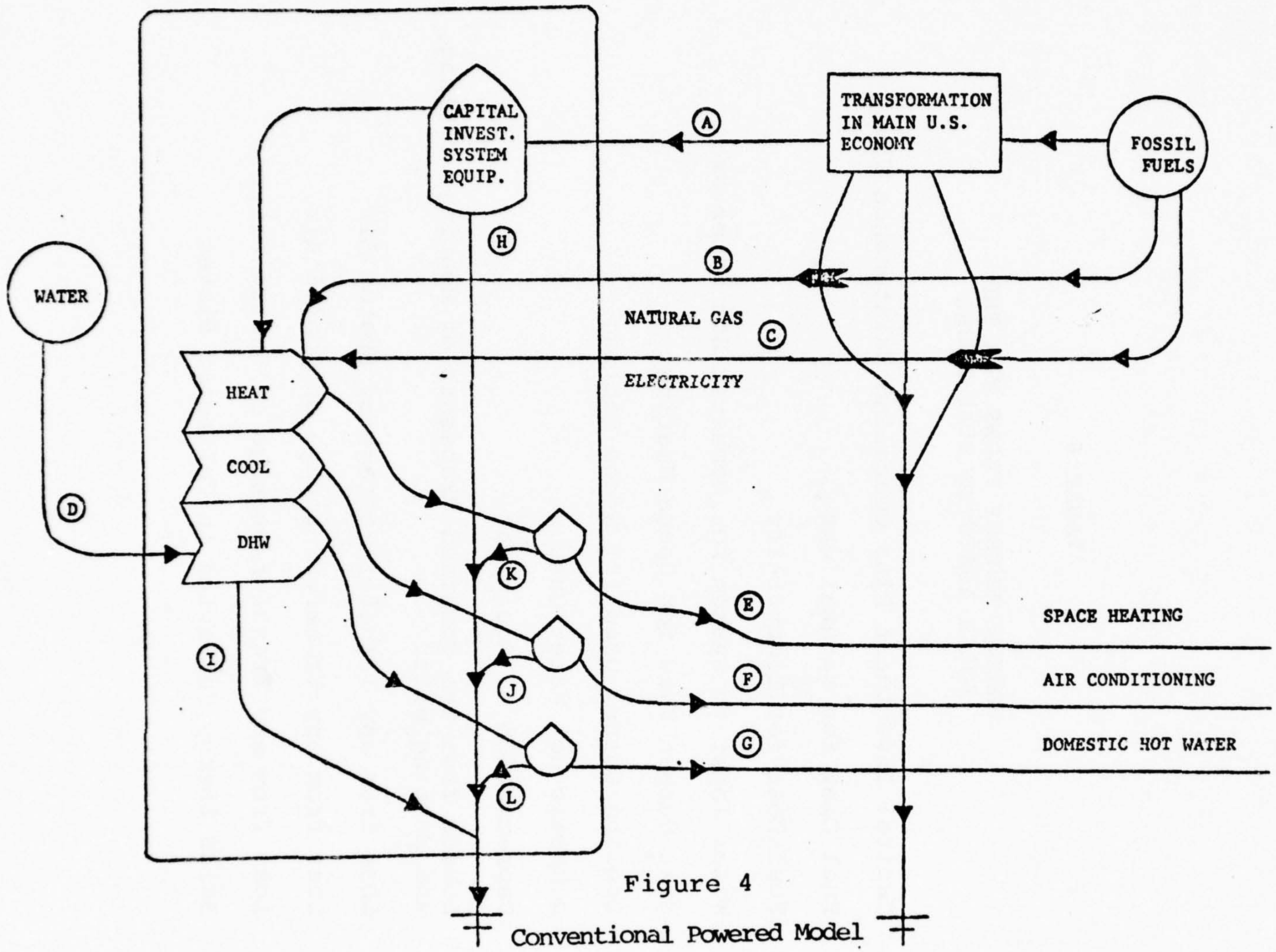

Figure 4
Conventional Powered Model

TABLE 7

ANNUAL ENERGY FLOWS FOR THE CONVENTIONAL MODEL

A. Capital Investment Plus Operating Maintenance Cost

B. Fuel Cost for Natural Gas

C. Fuel Cost for Electricity

D. Water Input to System for Domestic Hot Water Use

E. Heat Output Used for Space Heating

F. Cooling Output Used for Space Cooling

G. Domestic Hot Water Output

H. Depreciation of Equipment

I. Combined Losses from Heating, Cooling, DHW Processes

J. Loss from Transfer/Storage of Cooled Air

K. Loss from Transfer/Storage of Heated Air

L. Loss from Transfer/Storage of Heated Water

procedure which formed the basis for a more powerful and accurate procedure. This latter transformation procedure, developed by Bullard at the University of Illinois at Champaign-Urbana, is the most advanced of the procedures reviewed by the researchers (3:1-28). Consequently, Bullard's procedure is used exclusively in this research effort.

Net energy analysis can be applied to actual situations in several ways: the process analysis, the input-output (I-O) analysis, or the hybrid analysis. The process analysis first requires a listing of all the components of the system to be analyzed (3:4-6). Calculations of the energy necessary to fabricate each component of the system are then made, with the sum of these calculations representing the total amount of energy required to construct the entire system. The process analysis, while sound from a theoretical viewpoint, is cumbersome to apply in real situations due to the explicit enumeration and calculations for all the components of a system.

I-O analysis reduces the amount of detail involved in the energy calculations. The U.S. Department of Commerce's Bureau of Economic Analysis (BEA) has divided the diverse U.S. economy into 368 different sectors, which I-O analysis is based upon. Associated with each of these sectors is an energy coefficient which represents the amount of energy necessary to produce the goods or service

contained within a particular sector (3:11-12). The energy coefficients corresponding to a sector are listed in units of BTUs of various qualities (coal, crude oil, electricity, etc.) per 1967 dollar value of the goods or services. This energy unit was chosen because it allows the grouping of an associated array of goods or services into a single economic sector without specifically addressing differences of size, capacity, features, and components among goods and services within the sector. Since the energy unit is based upon a 1967 dollar value, a price index is used to counteract the devaluation effect inflation has on current dollars.

The I-O analysis falters whenever a component of the system to be analyzed cannot be associated with any of the economic sectors outlined by the BEA. This situation frequently occurs when one analyzes systems containing state-of-the-art or very recently developed systems. To cope with this situation, the hybrid analysis is employed by first listing the major components of the atypical system (the process analysis orientation). Next, one applies the I-O analysis by assigning each of the previously identified major components of the system into one of the economic sectors. From this point on, the hybrid analysis is identical to the I-O analysis.

While the use of the process, I-O, and hybrid analyses are valid, one should be aware of the limitations and uncertainties of their use. First, the price of a good

or service may change over time (3:13). Although the price indexes attempt to correct for fluctuating price levels, these indexes may not always be accurate and may not precisely conform to the BEA sector definitions. Second, the structure of the economy varies rapidly with the changing technology for producing goods and services. Recent studies are examining methods to modify net energy analysis to reflect variations in technology (3:13). Third, the use of sector aggregation is a less than optimal approach. Since the U.S. economy produces millions of goods and services, it is infeasible to calculate an energy value for each good and service. To accomodate the diverse U.S. economy at the cost of some accuracy, many similar goods and services are grouped into a single economic sector (3:13). Fourth, economic and accounting conventions can cause inaccuracies because the cost data are collected from companies. These costs cover only the producer's cost and do not include wholesale and retail profit margins, transportation and insurance costs and capital investment (3:14). Fortunately, a tabulation of profit margins, and transportation and insurance costs has been completed, with costs determined as a percentage of the ultimate cost of the good or service to the customer. Considerations are made for capital investment in the energy coefficients associated with each sector. Finally, there are problems involved in the collecting and processing of a vast quantity

of data. These problems include

> Incomplete census coverage, reporting errors due to misunderstanding or outright lying, sampling errors inherent in surveys of firms, transcription or key punching errors, the possibility that forms are lost, calssification errors, and . . . the problems of separating companies from establishments in processing returns from surveys or census [3:16].

The energy analysis, presented in Appendix D, is performed with the cost information and format displayed in Table 8 and using the analytical techniques presented by Bullard.

Initially, the equipment listed in Table 8 must be placed in the most representative economic sector. All ductwork, generally made of sheet metal, was associated with sector 40.07, sheet metal work. The expansion tanks, cooling towers, and heat exchangers consist of heavy steel construction, and were subsequently associated with sector 40.06, fabricated plate work. Heat recovery equipment, air handling units, and water chillers are not associated with any specific sector. For this reason, they were placed in sector 49.07, general industrial machinery. The solar collector supports, not specifically discussed in the design report, are assumed to be made of steel, and are assigned to sector 40.04, fabricated structural steel. The maintenance and replacement activities, which contain a wide variety of items, were associated with sector 12.02,

TABLE 8

HVAC SYSTEMS EQUIPMENT AND COSTS (17)
(with Associated Economic Sectors)

	Sector	Conventional	Solar Heating/ Cooling
SYSTEM EQUIPMENT			
Plumbing	40.02	$ 59,800	$ 59,800
Ductwork (HVAC)	40.07	80,000	80,000
Ductwork (Heat Recovery)	40.07	1,000	1,000
Heat Recovery Equipment	49.07	1,000	1,000
Expansion Tanks	40.06	1,200	1,200
Exhaust/Outside Air Fans	49.03	1,750	1,750
Cooling Towers	40.06	9,000	9,000
Air Handling Units	49.07	35,200	35,200
Solar Collectors		-0-	147,050
	40.04	-0-	102,124
Water Chillers	49.07	33,000	61,000
Heat Exchangers/Piping	40.06	35,000	81,455
Heating Equipment	40.03	3,300	7,800
Pumps	49.01	1,350	3,350
Controls	53.05	25,000	35,000
Insulation	36.18	20,000	34,090
OWNING/OPERATING COSTS			
Maintenance	12.02	$ 198,525	$427,868
Operating		1,405,177	266,282
Replacement			
(10, 20, 30 yrs)	12.02	14,569	23,819
(20 yrs)	12.02	117,439	106,470

general maintenance and repair. The remaining entries in Table 8, except solar collectors and operating costs, are typical manufacturing products and are assigned to their associated sectors, as shown. The operating costs, composed entirely of fuel costs, need not undergo a dollar/energy transformation as the fuel already represents energy; it merely requires a quality conversion to coal equivalents (CE), which will be used exclusively in this analysis.

The solar collectors, an atypical product, must be broken down into major components and treated with a process analysis. Glass plates, copper tubing, steel casing, aluminum absorber plate, and fiberglass insulation are considered to be the major components of the solar collectors. The sectors into which these components are assigned are as follows:

Glass plates:	Glass products	35.01
Copper tubing:	Copper rolling and drawing	38.07
Steel casing:	Sheet metal work	40.07
Aluminum absorber plate:	Miscellaneous metal work	40.09
Fiberglass insulation:	Gaskets and insulation	36.18

The aluminum absorber plate was assigned to the miscellaneous metal working sector instead of a purely aluminum sector because aluminum strips are mechanically bonded to the absorber plate over the 3/8 inch copper tubing.

Once the items in Table 8 have been assigned a sector, the energy analysis calculations for each item require several pieces of additional information, as seen

in Appendix D. The sector, cost, price index, and margins for each item are displayed along with energy equations for the sector and each margin. Holding the first position in the equations is the cost of the item being analyzed. The equations for the margins (rail or truck transportation and wholesale or retail trade) contain in second position the percentage of the total cost of the item devoted to that particular margin, followed by the price index and energy coefficient (in terms of BTU CE per 1967 dollar) for that margin. The equation for the item of interest contains in the second position the remaining percentage of the item's total cost not devoted to margins, followed by the price index and the energy coefficient for that item. Summing the results of the energy equations yields the energy required to produce a particular good or service.

The energy analysis of the solar collectors is treated slightly different than the other items. Since the prices quoted for the major components of the collector were on the wholesale level, retail margins for any of the individual major components were dropped. The retail margin (sector 69.02), however, was used in an aggregate manner to represent the retail mark-up of the entire collector, as seen in Appendixes D and E. Sector 11.05, new construction, was used to represent the labor necessary to assemble the solar collector.

System energy balance. The laws of thermodynamics reveal that every functioning system must achieve a balance of consumable energy flows through it. The inputs to a system must equal the outputs and losses from that system.

Previously the researchers identified the subsidy to the system in the area of capital investment (i.e., equipment, repair and maintenance). This area will not be considered in balancing the consumable energy flows in both HVAC systems. The next area considered is the conversion of all the fuel inputs, load demands and associated losses with each system into coal equivalents. The basic data available on these inputs and demands is contained in the Preliminary Design Report (see Tables 9 and 10). This data was obtained in a simulation of each system under similar conditions. The first assumption associated with this data concerns the demand loads for each system. Because of separate simulations, the demands vary slightly. To overcome this problem and to facilitate the comparison of the two systems, the output demand loads were assumed to be equal. The values in Table 9 are the output demands for each system.

In each HVAC system, there are three basic processes: (1) space heating, (2) domestic hot water (DHW) heating, and (3) air conditioning. For each of the processes, the direct and indirect energies to operate the processes were identified.

TABLE 9

CONVENTIONAL SYSTEM ENERGY ANALYSIS (17)
(Yearly Totals)

Total Cooling Load	214264 Ton-Hrs.
Total Heating Load	385411 MBTU
Total Chiller Input	198249 KWH
Total Boiler Output	385411 MBTU
Total Domestic Hot Water Output	134564 MBTU
Yearly Electrical Usage	531827 KWH
Yearly Gas Usage	693330 MBTU

TABLE 10

SOLAR HEATING AND COOLING SYSTEM
ENERGY ANALYSIS (17)
(Yearly Totals)

Total Cooling Load	175877	Ton-Hrs.
Total Heating Load	232589	MBTU
Total Heat Collected	2061637	MBTU
Total Ht. Pump Input (Cooling)	71520	KWH
Total Ht. Pump Input (Heating)	659	KWH
Auxiliary Equip. Electrical Input	594407	KWH
Total Supplemental Heating	0	MBTU
Total Domestic Hot Water Output	5316	MBTU
Yearly Electrical Usage	666586	KWH
Yearly Fuel Usage	7088	MBTU

	Direct	Indirect
Space Heating	Gas	Electric
DHW	Gas	Electric
Air Conditioning	Electric	Electric

It can be seen that with each process, an amount of electric energy is needed to operate the process. Looking at the total HVAC system, the indirect electric energy can be associated with the operation of an array of pumps, controls, and fans that comprise the total HVAC system. The energy flow is separated and designated as auxiliary electric power.

The energy balance for the conventional system was calculated first. The demand loads were given and accepted as the average operation conditions. The conversion of the demand loads was accomplished in Appendix F. The approach used in identifying and developing the specific energy flows and values centered around the data available in the Preliminary Design Report and the basic concepts involving the operation of the different processes. In establishing specific inputs and outputs, the resulting effort helped in identifying and assigning values to the associated process losses. Losses were identified and assigned values in the following areas:

(1) air conditioning losses
(2) space heating loss
(3) DHW loss
(4) auxiliary electric power

Auxiliary electric power is classified as a loss because it is an indirect energy flow that does not directly impact on the three processes that comprise the total HVAC system. The auxiliary electric power operates the secondary functions associated with the HVAC system. The conventional HVAC model is displayed as a diagrammic model with the flows expressed in coal equivalent values shown in Figure 5 and Table 11.

The energy balance for the solar system was calculated next. The output flows were taken from the conventional system calculations. A major problem developed because, in this system, an additional energy flow was introduced and none was eliminated, thus giving the system three inputs: natural gas, electricity, and solar energy. This compounded the problem that was encountered evaluating the conventional system: the separation of the inputs and associating them with a specific process. Through analyzing the system, its functions, and the input and output data taken from the Preliminary Design Report (Tables 9 and 10), the following assumption was developed: the solar contribution to the air conditioning process was considered to be insignificant both in terms of magnitude and effectiveness, while the solar contribution to the space heating and DHW processes was approximately 100% both in magnitude and effectiveness. The yearly natural gas consumption was reduced drastically and, by further examining the Preliminary Design Report

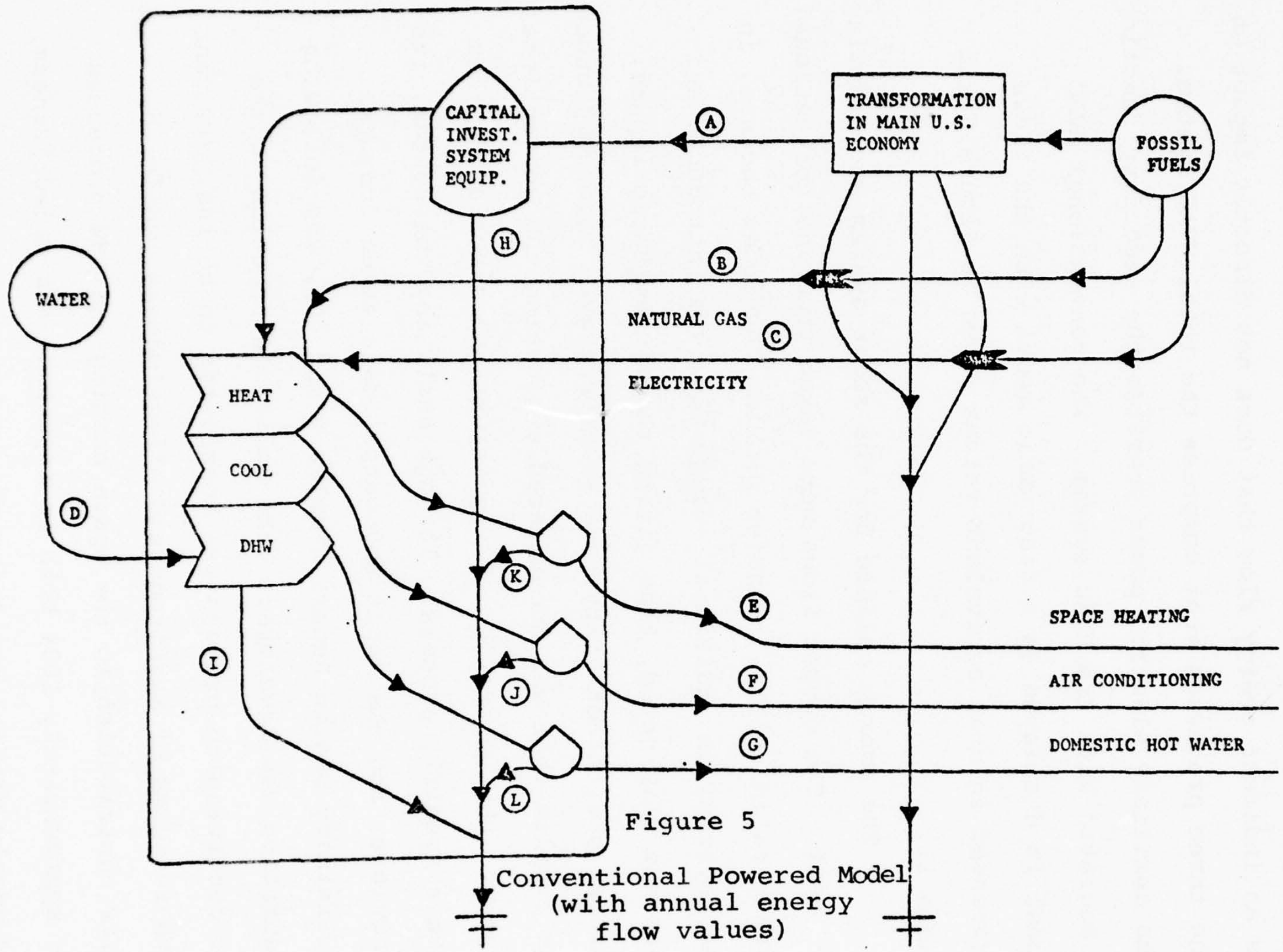

Figure 5

Conventional Powered Model
(with annual energy
flow values)

TABLE 11

ANNUAL ENERGY FLOW VALUES FOR
THE CONVENTIONAL MODEL
(BTU CE)

A.	Capital Investment Plus Operating Maintenance Cost	2.524×10^{8}
B.	Fuel Cost for Natural Gas	7.765×10^{6}
C.	Fuel Cost for Electricity	3.67×10^{9}
D.	Water Input to System for Domestic Hot Water Use	2.02×10^{5} gallons
E.	Heat Output Used for Space Heating	4.317×10^{6}
F.	Cooling Output Used for Space Cooling	1.038×10^{9}
G.	Domestic Hot Water Output	1.507×10^{6}
H.	Depreciation of Equipment	2.524×10^{8}
I.	Combined Losses from Heating, Cooling, DHW Processes	2.632×10^{9}
J.	Loss from Transfer/Storage of Cooled Air	3.29×10^{8}
K.	Loss from Transfer/Storage of Heated Air	1.44×10^{6}
L.	Loss from Transfer/Storage of Heated Water	$.503 \times 10^{6}$

data, the only use of natural gas was associated with the DHW process. The additional electricity associated with the solar system was placed in the auxiliary electric power flow as an indirect energy source.

The solar contribution to the space heating and DHW processes was combined and analyzed with the small amount of natural gas input. The demands less the natural gas input resulted in the total output needed to be supplied by the solar process. Two factors in the solar thermal process were considered: (1) the loss associated with the heat storage tank (approximately 10%), and (2) the efficiency of the solar thermal process in the collector to the tank (approximately 65%). *Using these factors and the* known solar contribution to the outputs, the calculations were worked backwards to determine the net solar energy captured by the solar collector needed to operate the system and to calculate the values for the losses in the process. The solar assisted HVAC model is displayed as a diagrammic model with the flows expressed in coal equivalent values shown in Figure 6 and Table 12.

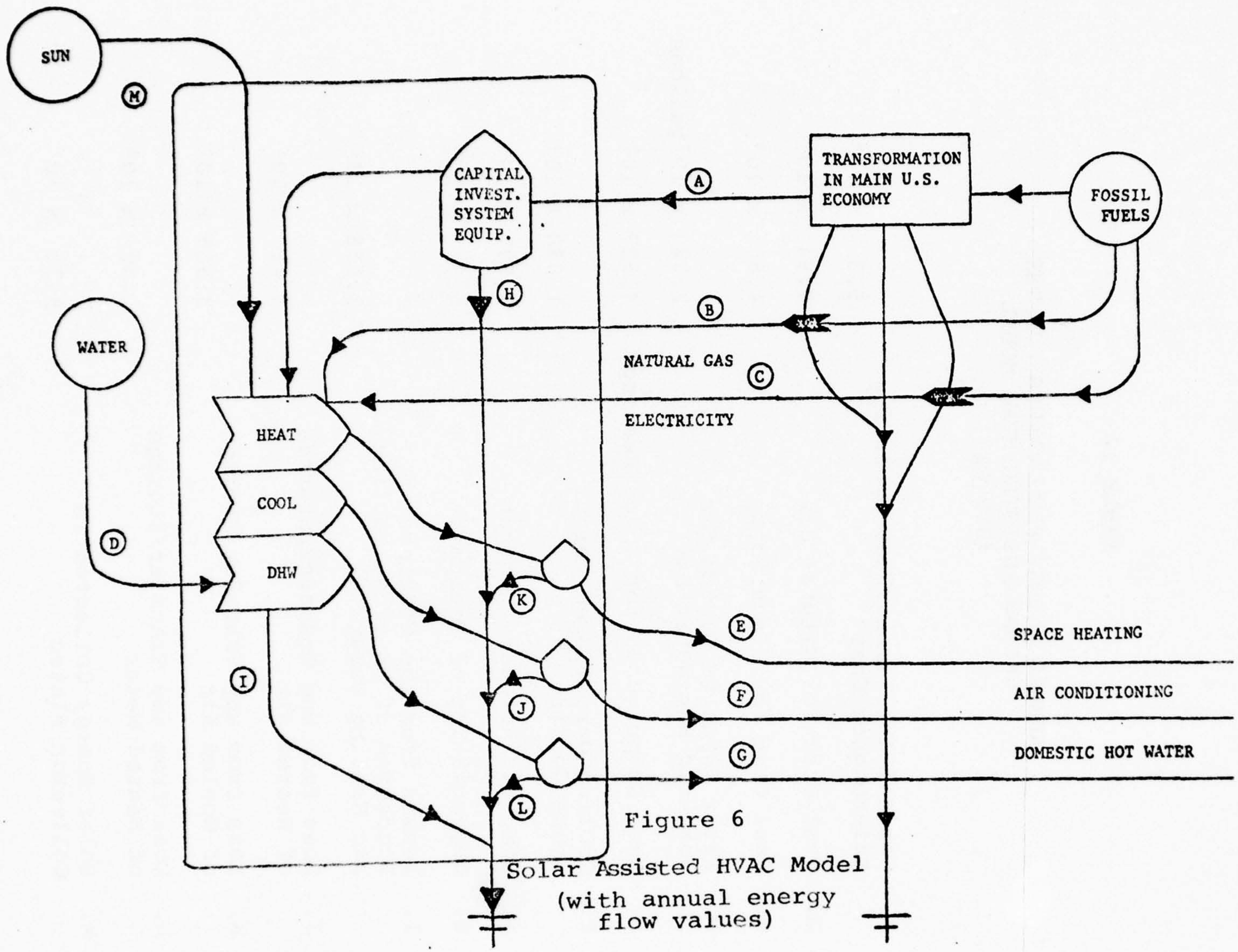

Figure 6

Solar Assisted HVAC Model
(with annual energy
flow values)

TABLE 12

ANNUAL ENERGY FLOW VALUES FOR THE SOLAR ASSISTED HVAC MODEL (BTU CE)

A.	Capital Investment Plus Operating Maintenance Cost	5.3×10^{8}
B.	Fuel Cost for Natural Gas	7.94×10^{4}
C.	Fuel Cost for Electricity	4.6×10^{9}
D.	Water Input to System for Domestic Hot Water Use	2.02×10^{5} gallons
E.	Heat Output Used for Space Heating	4.317×10^{6}
F.	Cooling Output Used for Space Cooling	1.038×10^{9}
G.	Domestic Hot Water Output	1.507×10^{6}
H.	Depreciation of Equipment	5.3×10^{8}
I.	Losses from the Combined Processes of Heating, Cooling, and Heating Water	3.566×10^{9}
J.	Loss from any Transfer/Storage of Heated Air	3.41×10^{6}
K.	Loss from any Transfer/Storage of Cooled Air	3.566×10^{9}
L.	Loss from any Transfer/Storage of Heated Water	$.58 \times 10^{6}$
M.	Solar Energy Collected in Collector Plates	9.75×10

Economic Model

The Preliminary Design Report prepared by the Clifford S. Nakata & Associates Consulting Firm utilized a Life Cycle Cost (LCC) Desk Calculation Method to evaluate the feasibility of a solar assisted heating, ventilation and air conditioning system with an additional capability for supplying DHW for the facility. In the economic analysis the following cost areas are looked at: (1) projected fuel costs for fuel oil, electricity, and natural gas; (2) equipment included in the different systems; (3) operation and maintenance of the systems; and (4) replacement of equipment during life of facility. The report compares the most economic of the fossil fuel systems to a solar system. The researchers will state the assumptions made in the calculation of values for the analysis in each of the cost areas mentioned above.

The fuel costs and the procedure used in calculating them are presented in Appendixes A and B. In general, the main emphasis is to develop a reasonable estimate of the growth of the primary fuel costs that can be used to power the HVAC system. The projection for the fuel is to extend for the life of the facility, which is 35 years. The report initially selected fuel oil as the primary fuel for this system but, in a later report, they were directed to use natural gas as the main fuel. The assumption concerning the rates at which fuel costs will increase, which vary

according to the fuel, is the most critical assumption in the analysis. As the fuel rates increase, the solar system begins to look increasingly more cost effective. The most reliable and acceptable rate should be used to avoid prejudicing the final analysis.

The second area addressed in the report is the equipment involved in the system. The report lists common items between the conventional and solar systems. The cost for these common items becomes the basic cost of the system. The costs of additional equipment needed to construct the solar system are classified as premium costs. The premium costs are significant because the basic costs include a back-up system capable of satisfying 100% of the maximum demand on the system. Therefore, the solar system is an additional system applied to the basic, conventional system. This cost area contains no assumptions because the determination of costs is for the present timeframe.

The third area deals with the operation and maintenance costs for the individual systems over the 35 year period, specified in the Preliminary Design Report as the life of the facility. This report makes an assumption to determine yearly costs and to project these costs into the future 35 year period. This assumption is that yearly maintenance costs are approximated at 1% of the initial construction cost and is escalated at 5% per year. In the operational cost area, the range of projected fuel costs

were averaged and multiplied by the 35 year period. This operation produces the total operating fuel cost for the system.

The last cost area deals with the equipment replacement during the 35 year life of the system. For each system, a list of replacement items is developed. There are two groups of equipment, each having their own replacement cycle. The cycles are: (1) a replacement at 10, 20, 30 years, and (2) a replacement at 20 years. The cost for these replacement items takes into account the time period in which they are replaced and are calculated accordingly.

In summary, the basic economic analysis follows a reasonable, documented approach (the LCC desk calculating method). The assumptions are generally acceptable and no problems are seen with them. One exception is the assumption in the projection of fuel costs. Great care and judgment should be exercised in developing these projections because they have a significant impact on the decision between the conventional system versus the addition of a complete solar system to the conventional system.

Chapter 4

ANALYSIS

Net Energy Analysis

With the energy balance for each HVAC system completed, net energy analysis could be applied to each system. The net energy analysis is composed of three principal measures: the net energy, the net energy yield ratio and the investment ratio. Using these three measures the systems can be compared and evaluated using energy as the common denominator.

The input flows for each system must be assigned to either of two categories:

- Category I - the energy value of material, environmental, and processed energy subsidies.

- Category II - the external energy sources that have a direct relation to the energy outputs.

The flows were assigned to either category as follows:

Category I: Subsidies (Feedback)

Solar	Conventional
Capital Investment	Capital Investment
Auxiliary Electric	Auxiliary Electric

Category II: Direct Inputs (External Sources)

Solar	Conventional
Natural Gas	Natural Gas
Electricity	Electricity
Solar	

In the conventional system, it was determined that the direct input energy consisted of the electric input to the air conditioner chiller unit and all the natural gas. The remaining electric input was labeled auxiliary electric and considered as a subsidy to the direct operation of the HVAC system. Looking at the solar system, it was determined that solar energy was a direct input to the system. Solar energy impacted significantly in offsetting inputs of natural gas. In viewing net energy analysis theory, it was determined by the researchers that solar energy is not the only direct input to the solar HVAC system. The electricity used in the air conditioner chiller unit and any supplemental natural gas are also direct inputs because they are involved in the direct conversion to the output energy forms.

Net energy is defined as the difference between yield (output) and feedback (24:257). The net energy yield ratio is defined as the ratio between yield (outputs) and feedback (24:259). The application of net energy and the net energy yield ratios are displayed in Tables 13 and 14.

The investment ratio is another measure in net energy analysis. The investment ratio is defined as the

ratio between the feedback (subsidies) and external sources (direct inputs) (24:263). Using the classification of the inputs and subsidies presented earlier, the ratios can be seen in Tables 13 and 14.

In comparing the net energy of each system, the results show that the conventional HVAC system is the more net energy effective of the two systems. The net energy values in this specific case are both negative, but the conventional system value is less negative than the solar value.

Comparison of Net Energy

Conventional: $- 1.8406 \times 10^9$ BTU CE

Solar : $- 3.0522 \times 10^9$ BTU CE

The conventional system does not require as great a subsidy to produce the same amount of output.

In comparing the yield ratios of the conventional system and solar system strictly, the results show that the conventional HVAC system is more net energy effective than the solar HVAC system.

Comparison of Yield Ratios

Conventional: .3600

Solar : .2548

The conventional system is not really a good net energy effective system, but is better than the alternative (solar).

TABLE 13

CONVENTIONAL HVAC SYSTEM'S ENERGY FLOWS BY CLASSIFICATION AND NET ENERGY ANALYSIS RESULTS

(BTU CE)

External Sources: Direct Inputs	
Natural Gas	7.756×10^{6}
Electric Power to A/C Chiller	$\underline{1.038 \times 10^{9}}$
	1.0458×10^{9}
Feedback: Subsidies	
Capital Investment (Equipment)	2.524×10^{8}
Auxiliary Electric	$\underline{2.632 \times 10^{9}}$
	2.8844×10^{9}
Yield: Outputs	
Heating	4.317×10^{6}
Cooling	1.038×10^{9}
DHW	$\underline{1.507 \times 10^{6}}$
	1.4038×10^{9}

Net Energy:

$$\text{OUTPUTS} - \text{SUBSIDIES} = 1.0438 \times 10^{9} - 2.8844 \times 10^{9}$$
$$- 1.8406 \times 10^{9}$$

Yield Ratio:

$$\frac{\text{OUTPUTS}}{\text{SUBSIDIES}} = \frac{1.0438 \times 10^{9}}{2.8844 \times 10^{9}} = 0.36$$

Investment Ratio:

$$\frac{\text{SUBSIDIES}}{\text{DIRECT INPUTS}} = \frac{2.8844 \times 10^{9}}{1.0458 \times 10^{9}} = 2.76$$

TABLE 14

SOLAR HVAC SYSTEM'S ENERGY FLOWS BY CLASSIFICATION AND NET ENERGY ANALYSIS RESULTS

(BTU CE)

External Sources:	
Solar	9.75×10^{6}
Natural Gas	7.94×10^{4}
Electricity	1.038×10^{9}
	1.048×10^{9}
Feedback: Subsidies	
Capital Investment (Equipment)	5.30×10^{8}
Auxiliary Electric	3.566×10^{9}
	4.096×10^{9}
Yield: Outputs	
Heating	4.317×10^{6}
Cooling	1.038×10^{9}
DHW	1.507×10^{6}
	1.0438×10^{9}

Net Energy:

$$\text{OUTPUTS} - \text{SUBSIDIES} = 1.0438 \times 10^{9} - 4.096 \times 10^{9} = -3.0522 \times 10^{9}$$

Yield Ratio:

$$\frac{\text{OUTPUTS}}{\text{SUBSIDIES}} = \frac{1.0438 \times 10^{9}}{4.096 \times 10^{9}} = .2548$$

Investment Ratio:

$$\frac{\text{SUBSIDIES}}{\text{DIRECT INPUTS}} = \frac{4.096 \times 10^{9}}{1.048 \times 10^{9}} = 3.91$$

In comparing the investment ratios strictly, the results show that the conventional HVAC system has a better investment ratio than the solar system because, for every unit of direct energy input, there was an investment of 2.76 units of energy, whereas in the solar system, there was an investment of 3.91 units of energy.

Comparison of Investment Ratios

Conventional: 2.76

Solar : 3.91

Therefore, the immediate conclusion drawn from this data is that the conventional system is the better of the two systems in terms of net energy. This result contradicts the results of the economic (LCC) analysis which recommended the solar system over the conventional system.

Economic Analysis

The economic analysis consisted of a Life Cycle Cost Study of each system. The comparison of the two systems is displayed in Table 15. The basic cost for each system is the same value. The reason for this is the requirement that the backup system for the solar system be capable of meeting 100% of the demand facilitated the use of the same complete system that makes up the conventional system. The equipment is similar to both systems.

TABLE 15

LIFE CYCLE COST COMPARISON OF THE CONVENTIONAL AND SOLAR HVAC SYSTEMS (17)

System	Conventional	Solar Heating/ Cooling
BASIC COST		
Plumbing	$ 59,800	$ 59,800
Ductwork (HVAC)	80,000	80,000
Ductwork (Heat Recovery)	1,000	1,000
Heat Recovery Equipment	1,000	1,000
Expansion Tanks	1,200	1,200
Exhaust/Outside Air Fans	1,750	1,750
Cooling Towers	9,000	9,000
Air Handling Units	35,200	35,200
	$ 188,950	$188,950
HVAC (PREMIUM) COST		
Solar Collectors	-0-	$147,050
Collector Supports	-0-	102,124
Water Chillers	$ 33,000	61,000
Heat Exchangers/Piping	35,000	81,455
Heating Equipment	3,300	7,800
Pumps	1,350	3,350
Controls	25,000	35,000
Insulation	20,000	34,090
	$ 117,650	$471,869
HVAC (PREMIUM) COST	(BASIS)	($354,219)
TOTAL INITIAL COST	$ 306,600	$660,819
PREMIUM HVAC COSTS	-0-	$867,695
OWNING/OPERATING COSTS		
Maintenance	$ 198,525	$427,868
Operating	1,405,177	266,282
Replacement		
(10, 20, 30 yrs)	14,569	23,819
(20 yrs)	117,439	106,470
TOTAL OWNING/OPERATING COST	$1,735,710	$824,439

The HVAC (premium) cost covers equipment peculiar to each system and the difference between the conventional cost and the solar cost is labeled as the premium cost. This premium cost is $354,219 over the conventional system.

The operating costs is the area in which the solar system has the most impact on costs. The costs of maintenance for the solar system is greater but, the operation costs are significantly less than those of the corresponding conventional system.

Operating Cost -	Conventional	Solar
	$1,405,177	$266,282

The difference is $1,138,895 over the 35 year period. This is an 81% reduction in operating costs. The operating costs are made up of the fuel costs for the systems over the 35 year period.

Comparison of Total Life Cycle Costs:

Initial Capital	$ 306,600	$ 660,819
Capital Recovery Cost	- 0 -	206,876
Total Initial Capital	$ 306,600	$ 867,695
Owning/Operating Costs	1,735,710	824,439
TOTAL	$2,042,310	$1,692,134

Because of the lower life cycle cost for the solar system, it was recommended as the system to be incorporated into the BX facility.

In general, the additional costs involved with acquiring the solar system were offset by the reduction in the operating cost (natural gas fuel) over the 35 year period.

Comparison of Economic and Net Energy Analyses

From examining the economic analysis of and applying net energy analysis to the BX project, the researchers understand and appreciate more fully the characteristics of both analyses.

Economic analysis utilizes cost information for all components of a system. This cost information, representing the dynamic, diverse U.S. economy, is subject to unpredictable variations over time. Although these variations are a product of many variables, perhaps the most significant one is inflation. This highly volatile variable can render any economic analysis useless -- it distorts the cost information to such an extent that the dollar values no longer reflect the true costs of the system components. To compensate for the devaluating affect of inflation, the economic analysis increases the cost of system components purchased in the future by a fixed amount per year (i.e., 7% per year as used in the Fuel Cost Study in Appendix A). It must be realized that the results of the economic analysis may be very sensitive to this fixed rate of annual price increase.

The time value of money is a central concept of economic analysis which allows alternative systems to be compared equitably. This concept enables the grouping of all costs incurred during the life of systems to be translated to any point in time. Inflation, however, effects all costs incurred beyond the start-up of the system and must be dealt with as discussed above. Although cost information is generally easily obtained, only the initial system costs are precisely known.

Current policy in both governmental and industrial sectors of society promote the use of economic analysis based on the time value of money concept. In fact, economic considerations are commonly as significant a decision-making factor as the design considerations.

Net energy analysis is based upon energy rather than upon cost information within a system -- it focuses on identifying the flows of energy into, within, and from a system. In order to quantify these flows, however, the method employed by the researchers utilized cost data on the system components. Thus, net energy analysis is just as susceptible to some fluctuations in cost information as economic analysis is. Energy values for the flows, which are extremely difficult to calculate directly, are dependent upon cost and energy information in order to quantify them indirectly. The only energy flows that are not affected by the dynamic fluctuations discussed above are the outputs of

the system. The system outputs are determined from required design loads established for specified energy conversion processes.

Having applied net energy analysis to a real system, the researchers discovered several facets of the analysis in need of some improvement. Consequently, net energy analysis, a rather new conceptual orientation compared to economic analysis, is not fully understood, appreciated, or accepted by most governmental and industrial decision-makers. The net energy analysis procedure, an operational mechanism to achieve the efficient utilization of energy, is a valuable supplement to economic analysis in that it helps to identify and quantify energy concentrations associated with a system. Net energy analysis cannot currently be employed independent of economic analysis because more importance is associated with economic analysis by decision-makers.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The results and conclusion from the application of net energy analysis contradicts the conclusion determined by the economic analysis application. The net energy analysis conclusion recommended the development of the conventional powered HVAC system, whereas the economic analysis determined that the development of the solar powered system is the best alternative. The reasons for the difference can be seen by examining the basis of each evaluation. The result from the application of net energy analysis can be expressed in three evaluation measures derived from the net energy model. These evaluation measures are net energy, yield ratio, and investment ratio. The interpretation of these measures are the basis upon which a choice between competing system alternatives can be made.

The net energy of the HVAC system is the amount of energy outputs (heated air, cooled air, domestic hot water) minus the amount of energy subsidy to the HVAC system required to produce and operate the system (in the form of equipment and auxiliary electric energy). A negative net energy value was calculated for each HVAC system indicating

that the energy subsidy to each HVAC system exceeded the energy outputs from each system. In light of the net energy model results, the HVAC systems do not make good use of the fossil fuel energy flowing into the systems from the main economy.

The yield ratio also supports the contention that the HVAC systems are not net energy effective. For a system to be competitive, the ratio of the yield to the feedback energies must be relatively high (greater than one). With both yield ratios less than one, the HVAC systems require more energy (in the form of subsidies) to operate than the energy contained in the outputs. Obviously, both HVAC systems do not utilize the energy they consume in a desirable fashion: precious fossil fuel energy is processed to supply an equivalently lesser amount of energy output (heated air, cooled air, domestic hot water).

The investment ratio, consisting of the ratio of feedback to direct input energies, should be relatively low for a competitive system. This suggests that for every energy unit utilized to drive the conversion process of the HVAC system, the energy required to subsidize those processes should be as low as possible. With investment ratios greater than one, the HVAC systems require an investment of more than one energy unit (in the equipment and maintenance of the BX facility) for the use of one energy unit -- clearly not a competitive proposition. However, the usual investment

ratio for systems in the U.S. is 2.5 and it is considered to be the upper limit for attractive investment ratio (24:263). Since the investment ratios of the two HVAC systems exceed this upper limit, they are not considered competitive systems from the standpoint of their energy utilization. However, if the decision-makers were to chose between these two alternative systems using this information, they would select the conventional HVAC system because it utilizes energy resources more efficiently (a higher yield ratio and lower investment ratio) than the solar system.

The economic analysis developed in the Preliminary Design Report arrives at precisely the opposite conclusion as it recommends the solar HVAC system over the conventional system. Primarily due to substantially lower fuel costs, the solar system is able to show a lower life cycle cost over the 35 year life of the BX facility compared to the conventional system. Thus, the solar HVAC system utilizes fewer dollars to satisfy the energy requirements of the BX facility, thereby rendering it the more economically competitive system.

To better determine which HVAC system to develop, the decision-makers must utilize the evaluation of both the economic and net energy analyses. Since the analyses support the development of different systems, the decision-makers must determine if energy considerations are of a higher significance to the decision than the economic

considerations. The solar system (economic analysis results) would most likely be recommended because economic considerations are currently regarded as more significant than energy utilization considerations. This gives rise to the following questions: does society want to save energy (in all forms that are irreplaceable) or does society only want to save the economic cost of energy utilization? Today, saving energy is the reduction of energy costs which are directly associated with an energy source (coal, natural gas, or petroleum). If this approach to saving energy changes to one of analyzing the total utilization of the irreplaceable energy sources, then there is a place for net energy analysis in the decision-making process.

Recommendations

As demonstrated, net energy analysis can be applied to real systems. The researchers believe that several facets of net energy analysis should be addressed and clarified in order to facilitate its application to a wide variety of systems.

First, in developing energy values for goods and services, the method used should be capable of being applied without a tremendous amount of effort or calculations. One of the two methods currently available does not fall into this category. The process analysis method analyzes all energies consumed in individual processes but

the application of this technique requires much effort and extensive research to develop the energy coefficients and energy values.

The I-O method uses energy coefficients that represent an aggregated group of goods and services (BEA sector). It utilizes the costs of the goods or services being analyzed and the associated BEA sector energy coefficients to develop the energy values. The hybrid method used in this research combines the process and I-O analyses.

But net energy analysis analytical techniques should not be totally reliant upon cost information in order to determine energy values for goods and services. According to the theory, net energy analysis attempts to divorce itself from dollar values to avoid the inherent inflationary problems with them. However, the current state-of-the-art analytical technique employed utilizes the very cost information that net energy analysis attempts to avoid. Thus, net energy analysis is just as subject to errors caused by fluctuations in dollar values as is traditional economic analysis, although the former attempts to compensate for these fluctuations with price indexes.

Another problem relating to the energy coefficients used in the calculation of the energy values in the net energy analysis is that they are also subject to dynamic change with time. The reasons for this change are:

(1) technological advances, realized after the establishment of specific energy coefficients, could reduce the amount of energy required to produce a product or service by altering the production process, and (2) the energy sources required in the production processes could increase significantly because more energy intensive subsidies must be used to obtain the same product. Therefore, the energy values that are calculated with the energy coefficients are not as stable through time as stated in the theory. It is recommended, therefore, that further studies be initiated to develop a comprehensive tabulation of energy coefficients independent of any cost information while also accounting for the changing amount of energy consumed in a process over time.

Second, the explanation of the terms feedback (subsidy) and direct input energies should be further defined so as to be better able to distinguish between them. Applying the net energy approach to this specific project resulted in some difficulty determining which input should be identified as feedback energy and which should be identified as a direct energy input. Feedback energy is defined as the energy required to produce, develop, and upgrade the energy source being converted (12:1051). Current literature reviewed concerning net energy has not applied net energy to as complex a system (multi-fueled,

multi-process, multi-output) as that which the researchers analyzed. After some deliberation, the following was accepted as being the interpretation of feedback and direct input energies for the two HVAC systems analyzed. The capital investment (equipment) and auxiliary electricity compose the feedback energy while the annual chiller electrical input and natural gas usage are considered the direct input energy for the conventional system. For the solar system, the feedback energy consisted of the capital investment (equipment) and auxiliary electricity while the direct input energy was the total solar energy collected, natural gas, and chiller electrical input. It is recommended that the meanings of the terms feedback and direct input energies be further explained and operationally defined in such a way that there is little doubt as to their meanings and applications.

Third, the use of design energy data for an economic evaluation of a system is considerably different than for a net energy evaluation. In the economic analysis, the focus of the design energy data are on consumption -- in order to determine the costs of energy. The net energy analysis, however, uses the design energy data to concentrate on the utilization of energy -- in order to determine where energy is consumed in the system. Consequently, more detailed data collection is required for the net energy analysis of complex systems so that the multiple input,

process, and output system can be analyzed. In this research effort, net energy analysis quantified all energy flows associated with the system. In the Randolph BX project, the energy data available were of insufficient detail to readily identify the specific energy flows to a specific process. This problem is primarily the result of the HVAC systems utilizing several energy sources to produce a mixture of outputs. The amount of energy that each source (electric, natural gas, solar) contributed to produce an output (cooled air, heated air, DHW) could not be directly determined from the annual energy summaries contained within the Preliminary Design Report. To overcome this problem, assumptions were developed concerning the efficiencies of processes, the losses from processes, and the meaning of the energy data itself in order to perform an energy balance on each system. Thus, it is recommended that the format in which the energy information is collected be modified to include the amount of energy each source devotes to the production of each output.

Fourth, the methods used to develop the quality of the outputs of a system should be improved so that the quality of individual outputs (cooled air, heated air, DHW) can be more accurately determined. In this research effort, an assumption is that the quality of the outputs could be determined by equating them to the quality of the energy form most closely associated with its production. This

determination of quality necessitated another assumption identifying which energy source contributed significantly to the production of that output. It is recommended that a tabulation of quality conversion factors be developed covering a wide variety of process outputs.

Fifth, before net energy analysis becomes widely accepted as a management tool, managers and policy-makers at all organizational levels must recognize that the wise utilization of energy is one of their prime responsibilities. Once these and other recommendations are implemented to correct the deficiencies of net energy analysis, managers will possess a demonstrated, documented evaluation technique to apply to virtually any system. It is recommended that this refined net energy analysis be conscientiously applied by both governmental and industrial managers to all aspects of planning and development of systems in conjunction with traditional economic analysis in order to equitably shape the pattern of development and use of energy within the United States. If net energy analysis is widely accepted nationally, it could very possibly supercede economic analysis as the dominant planning consideration in the development of future systems.

APPENDIX A

FUEL COST STUDY

Appendix A

FUEL COST STUDY

Fuel Cost/Availability (17)

Fuel cost data were obtained from base personnel during Pre-Design Conference/Site Visit Survey. The following data were received:

Year	Electric $/KW	Gas $/MCF	Oil $/Gal
1972	0.0069	0.22	0.11
1973	0.0074	0.47	0.18
1974	0.0107	1.11	0.28
1975	0.0209	1.22	0.34
1976 (July)	0.0273	1.74	0.38

Using these data as a basis, costs of fuel were calculated.

1. Natural Gas: Present costs (1976) are $1.74 per thousand cubic feet (1000 BTU/ft^3) or $2.32 per million BTU. In the year 2011, it is projected that costs will increase to $18.58 per MCF (thousand cubic feet) or $24.77 per million BTU. Natural gas is immediate to the site. Gas is anticipated to be available on a long term basis, but in limited supply and on priority demand.

2. <u>Fuel Oil</u>: Present costs are $0.38 per gallon or $3.62 per million BTU. In the year 2011, it is anticipated that costs will increase to $5.62 per gallon or $53.52 per million BTU used. Fuel oil is a fuel which will be in limited supply and sensitive to priority demands.

3. <u>Electricity</u>: Present costs are calculated to be $0.0273 per KW (kilowatt) hour or $7.993 per million BTU. Future costs in the year 2011 are anticipated to increase to $0.1778 per KW hour or $52.095 per million BTU. Of all energy sources (fossil fuel derived), electrical energy is considered the most reliable. The increasing use of coal as the generating fuel source and the abundant quantities of this fuel available within the United States establish this reliability.

In summary, natural gas is presently available to the property. Although it is the least expensive fuel available, it is questionable that it can be made available for use. Only oil and electricity are considered likely sources of heating energy for the site. Electrical costs are considered prohibitive. Therefore, fuel oil would be, by elimination, the back-up heating system energy source. However, by directive from base personnel via the Architect Office, instructions have been issued to provide a natural gas back-up system.

Comparative Fuel Costs (17)

The figures in Table 16 and the calculations below give the present rates (1976), past rates, and projected rates (2011) based on a 35 year life span.

1. Natural Gas: Natural gas can be expected to increase in cost at an annual rate of 7% per year, compounded (1000 Btu/ft^3). Although drastic price changes have occurred in this fuel cost during the past two to three years, it can be anticipated that through government regulation, rate increases will tend to stabilize at "normal" rates.

1976 Costs:	\$1.74	\$ 1.74/MCF
2011 Costs:	(1.74 x 10.6766)	\$18.58/MCF

Cost per Million

1976:

$$1.74 \frac{\$}{MCF} \times \frac{1}{0.75}(\text{efficiency}) = \$2.32/_{MMBTU} \text{ Demand}$$

2011 (MM = 1,000,000)

$$18.58 \times \frac{1}{0.75} = \$24.77/MMBTU$$

2. Fuel Oil: Petroleum products are anticipated to increase at an annual rate of 8% per year, a result of diminished supply and economic pressure.

1976 Costs:	\$0.38/gal	\$30.38/gal
2011 Costs:	(0.38 x 14.7853)	\$ 5.62/gal
	(140,000 BTU/gal)	

TABLE 16

FUEL COST ($/Million BTU)

Fuel	1975	2011	Percent Increase
Natural Gas	2.32	24.77	968
Fuel Oil	3.62	53.52	1378
Electricity	7.993	52.095	552

Cost per Million

1976

$$0.38\ \frac{\$}{gal} \times \frac{gal}{140{,}000\ BTU} \times \frac{1000\ MBTU}{0.75} = \frac{\$3.62\ DEMAND}{MMBTU}$$

2011

$$5.62\ \frac{\$}{gal} \times \frac{gal}{140{,}000\ BTU} \times \frac{1000\ MBTU}{0.75} = \frac{\$53.52}{MMBTU}$$

3. <u>Electrical</u>: Based on previous studies (Army Reserve Centers), electrical costs can be anticipated to increase at 5½ percent per year.

1976 Costs:	\$0.0273/KWH	\$0.0273/KWH
2011 Costs:	(0.0273 x 6.5138)	\$0.1778/KWH

Cost per Million

1976

$$\frac{0.0273}{KWH} \times \frac{KWH}{3413\ BTUH} \times 1000\ MBTU = \frac{\$\ 7.999}{MMBTUH}$$

2011

$$0.1778 \times \frac{1000\ MBTU}{3413} = \frac{\$52.095}{MMBTUH}$$

APPENDIX B

LIFE CYCLE COST ANALYSIS

Appendix B

LIFE CYCLE COST ANALYSIS (17)

This analysis was performed using the Desk Calculating Method (DCM), as described in "Criteria and Guidance for Life Cycle Cost (LCC) Analytical Methods."

<u>Basis:</u> 6.125% - 35 years

F_u 2.4496

Fuel escalation as noted under "Fuel Cost Study"

Maintenance Cost

F_a (5% - 35 yrs) 64.75

Cycle Costs Replacement

$$F_{c_1}(10,20,30) = 1.45 + 1.95 + \left(\frac{35-30}{10}\right)2.45$$

$$= 4.625$$

$$F_c(20\text{ yrs}) = \frac{(35-20)}{20}1.95$$

$$= 1.4625$$

<u>Premium Cost:</u>

Conventional System as basis

(HVAC COST-BASIS) x F_u = DIFF x 2.4496 = -0-

Solar

(445650-117650) x F_u = 328000 x 2.4496
= 803470

Owning Operating Cost

Maintenance. Yearly costs are approximated at 1% of initial cost (construction) and escalated at 5% per year. LCC initial cost is based on estimated total initial cost minus the cost of collectors and supports. Only minor maintenance costs are associated with these items and can be absorbed in "normal" maintenance estimated cost. Range of $255-$530 per month is reasonable.

Conventional

$$\$306600 \times 1\% = \$3066$$

$$3066 \times F_a = 3066 \times 64.75 = \$198525$$

Solar

$$\$660819 \times 1\% = \$6608$$

$$6608 \times F_a = 6608 \times 64.75 = \$427868$$

Operating costs. Operating costs are derived from Appendix A.

$$\text{Fuel Oil:} \quad \frac{3.62 + 53.52}{2} = \frac{\$28.57}{\text{MMBTU}}$$

$$\text{Electrical:} \quad \frac{7.999 + 52.10}{2} = \frac{\$30.05}{\text{MMBTU}}$$

$$= \frac{\$0.10255}{\text{KWH}}$$

Conventional

Heating: 693,300 MMBTU x $\frac{28.57}{\text{MMBTU}}$ (avg)

= $19807.6/yr x 35 yrs

= $693,265

Cooling: 198249 KWH x $\frac{0.1026}{\text{KWH}}$ (avg)

= 20340/yr x 35 yrs

= $711,912

693,265 + 711,912 = $1,405,177

Solar

Heating: (Heat Pump)

372 x 0.1026 = $38.17

38.17 x 35 yrs = $1335

(Boiler-Domestic Water)

4.845 x 28.57 = 138.45

138.45 x 35 yrs = + 4846

$6181

Cooling: 106328 x 0.1026

= 10909

10909 x 35 yrs =+$381824

$388005

Replacement:

Conventional:

10 years

Heating Boiler	-	$ 900
DW Boiler	-	900
Pumps	-	1,350
		$ 3,150 x 4.625 = $ 14,569

20 years

Air Handling Units	-	$35,200
Fans	-	1,750
Cooling Towers	-	9,000
Chillers	-	33,000
Pumps	-	1,350
		$80,300 x 1.4625 = $117,439

Solar:

10 years

DW Boiler	-	$ 1,800
Pumps	-	3,350
		$ 5,150 x 4.625 = $ 23,819

20 years

Air Handling Units	-	$35,200
Fans	-	1,750
Cooling Towers	-	9,000
Chillers	-	23,500
Pumps	-	3,350
		$72,800 x 1.4625 = $106,470

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Life Cycle Cost

	Solar	Solar-Modification
Surface ($11000\ ft^2$)	$129,400	($12500\ ft^2$)$147,050
Support	89,875	102,124
Piping	40,000	45,455
Insulation	30,000	34,090
	$289,275	$328,720
Premium	(Basis)	$ 39,445
Premium Cost (35 years) x 2.4496		$ 96,624

Operating/Owning

	Solar	Solar-Modification
Maintenance	-	-
Replacement	-	-
Operating:		
Cooling	$381,824	$256,828
Heating	6,181	9,454
	$388,005	$266,282
Total 35 yr Cost (Premium Operating/Owning)	$388,005	$362,906

Therefore, it is recommended that the solar collector surface be increased in area to 12,500 ft^2 net and decreased in angle to 15° with the horizontal. This is the most cost effective design.

TABLE 17

LIFE CYCLE COST COMPARISON OF THE CONVENTIONAL AND SOLAR HVAC SYSTEMS (17)

System	Conventional	Solar Heating/ Cooling
BASIC COST		
Plumbing	$ 59,800	$ 59,800
Ductwork (HVAC)	80,000	80,000
Ductwork (Heat Recovery)	1,000	1,000
Heat Recovery Equipment	1,000	1,000
Expansion Tanks	1,200	1,200
Exhaust/Outside Air Fans	1,750	1,750
Cooling Towers	9,000	9,000
Air Handling Units	35,200	35,200
	$ 188,950	$188,950
HVAC (PREMIUM) COST		
Solar Collectors	-0-	$147,050
Collector Supports	-0-	102,124
Water Chillers	$ 33,000	61,000
Heat Exchangers/Piping	35,000	81,455
Heating Equipment	3,300	7,800
Pumps	1,350	3,350
Controls	25,000	35,000
Insulation	20,000	34,090
	$ 117,650	$471,869
HVAC (PREMIUM) COST	(BASIS)	($354,219)
TOTAL INITIAL COST	$ 306,600	$660,819
PREMIUM HVAC COSTS	-0-	$867,695
OWNING/OPERATING COSTS		
Maintenance	$ 198,525	$427,868
Operating	1,405,177	266,282
Replacement		
(10, 20, 30 yrs)	14,569	23,819
(20 yrs)	117,439	106,470
TOTAL OWNING/OPERATING COST	$1,735,710	$824,439

APPENDIX C

ESTIMATION OF PRICE INDEXES

Appendix C

ESTIMATION OF PRICE INDEXES

The price indexes used in the energy analysis are used to convert dollars spent in the 1976 construction of the BX project to an equivalent amount of dollars in 1967. Since the indexes available to the researchers only span the five years from 1970 to 1974, the index for 1976 had to be estimated.

Simple Linear Regression (SLR) was the technique selected to estimate the 1976 index for the following reasons. First, with only five data points, the results from a time series forecasting method would be inconclusive. Second, the data tends to exhibit a rough linear trend over the short time span in question. Third, the computations involved in the SLR can be accomplished quickly and easily using a computer routine in the Statistical Package for the Social Sciences (18).

SLR is based upon the following four assumptions (5:530).

1. A linear functional expression is an appropriate model of the relationship between the dependent and independent variables.

2. The subset of an independent variable's values that corresponds to a dependent variable's values is distributed normally.

3. The standard deviation of the independent variable's values that corresponds to a given dependent variable's value is the same for all values of the dependent variable.

4. The dependent variable's values do not have a distribution and are considered to be fixed.

The sample regression equation can be expressed as

$$y_c = a + bx$$

where y_c is the estimated value of the dependent variable y, b is the constant (regression coefficient) by which all of the values of the independent variable x are multiplied, and a is a constant which is added to each case (5:530-531; 18:323). Using the least squares method, the estimators a and b can be represented as

$$b = \frac{n(\Sigma xy) - (\Sigma x)(\Sigma y)}{n(\Sigma x^2) - (\Sigma x)^2}$$

$$a = \bar{y} - b\bar{x}$$

where n is the number of paired observations of x and y, and $\bar{x}$ and $\bar{y}$ are the means of the independent and dependent variables, respectively.

A measure of the strength of the linear relationship between x and y is termed the coefficient of determination (R^2), which is a ratio of the variation in the dependent variable explained by the independent variable (18:314). The value of R^2 varies from zero to one. An R^2 value near

one indicates a strong linear relationship between the dependent and independent variables and an R^2 value near zero indicates a weak linear relationship between the dependent and independent variables.

The results of the computer SLR routine are presented in Table 18 . The R^2 values indicate that the assumption of a linear relationship between the price indexes and the years was a valid one as all the R^2 values are reasonably near one.

The dependent and independent variables in the SLR were the year of the price index (1970 through 1974, coded 1 through 5) and the price index itself, respectively. Since the price index for a group of related economic sectors is generally different from that of another, separate SLRs must be completed for each group. As seen in Table 19, there are eleven of these groups of related economic sectors. The estimated values of the 1976 price indexes for the related economic sectors are found as follows, using the data from Table 18.

11.05 , 12.02 : $\text{Index}_{1976} = 1.1648 + .1576(7) = 2.268$

35.01 : $\text{Index}_{1976} = 1.138 + .0642(7) = 1.587$

36.18 : $\text{Index}_{1976} = 1.0316 + .082(7) = 1.606$

38.07 : $\text{Index}_{1976} = .9874 + .1042(7) = 1.717$

40.01 ,..., 40.09 : $\text{Index}_{1976} = .9634 + .1024(7) = 1.68$

49.01 ,..., 49.07 : $\text{Index}_{1976} = 1.0311 + .0745(7) = 1.553$

53.05 : $\text{Index}_{1976} = 1.0027 + .0521(7) = 1.367$

65.01 : $\text{Index}_{1976} = 1.1459 + .0753(7) = 1.673$

65.03 : $\text{Index}_{1976} = 1.1049 + .0273(7) = 1.296$

69.01 : $\text{Index}_{1976} = .94 + .0972(7) = 1.62$

69.02 : $\text{Index}_{1976} = 1.1361 + .0559(7) = 1.527$

TABLE 18

REGRESSION ANALYSIS OF SELECTED PRICE INDEXES

Economic Sector Number	a	b	R^2
11.05 , 12.02	1.1648	.1576	.98732
35.01	1.138	.0642	.93936
36.18	1.0316	.082	.91238
38.07	.9874	.1042	.55155
40.01 , . . ., 40.09	.9634	.1024	.77383
49.01 , . . ., 49.07	1.0311	.0745	.81692
53.05	1.0027	.0521	.71308
65.01	1.1459	.0753	.88619
65.03	1.1049	.0273	.58432
69.01	.94	.0972	.85047
69.02	1.1361	.0559	.91106

TABLE 19

SELECTED PRICE INDEXES

(1967 = 1.00)

Economic Sector Number	Year 1970	1971	1972	1973	1974	1976 (est.)
11.05 , 12.02	1.349	1.473	1.603	1.779	1.984	2.268
35.01	1.209	1.279	1.316	1.359	1.490	1.587
36.18	1.128	1.210	1.255	1.304	1.491	1.606
38.07	1.223	1.158	1.161	1.270	1.688	1.717
40.01 ,. . ., 40.09	1.117	1.175	1.214	1.261	1.586	1.680
49.01 ,. . ., 49.07	1.139	1.185	1.215	1.260	1.474	1.553
53.05	1.085	1.114	1.120	1.147	1.329	1.367
65.01	1.172	1.359	1.389	1.422	1.517	1.673
65.03	1.122	1.182	1.203	1.155	1.272	1.296
69.01	1.095	1.120	1.163	1.278	1.502	1.620
69.02	1.197	1.268	1.280	1.327	1.447	1.527

APPENDIX D

ENERGY ANALYSIS FOR THE HVAC EQUIPMENT

Appendix D

ENERGY ANALYSIS FOR THE HVAC EQUIPMENT

TABLE 20

SELECTED ECONOMIC SECTORS AND ENERGY COSTS

Sector Title	Sector Number	Energy Cost (BTU CE/ 1967 $)
New Construction	11.05	26228
General Maintenance & Repair	12.02	14654
Glass Products	35.01	23050
Gaskets & Insulation	36.18	25830
Copper Rolling & Drawing	38.07	31782
Plumbing Fittings	40.02	28322
Heating Equipment	40.03	32581
Fabricated Structural Steel	40.04	69149
Fabricated Plate Work	40.06	55202
Sheet Metal Work	40.07	57995
Miscellaneous Metal Work	40.09	79388
Pumps & Compressors	49.01	24506
Blowers & Fans	49.03	27466
General Industry Machinery	49.07	28150
Industrial Controls	53.05	15875
Railroad Transportation	65.01	15178
Motor Freight Transportation	65.03	7739
Wholesale Trade	69.01	6877
Retail Trade	69.02	8627

TABLE 21

MARGINS FOR SELECTED ECONOMIC SECTORS

Sector		Margin (Percent of Purchase Price) Rail Transportation [65.01]	Truck Transportation [65.03]	Wholesale Trade [69.01]	Retail Trade [69.02]
Glass Products	35.01	0	1	5	31
Gaskets & Insulation	36.18	8	0	5	2
Copper Rolling & Drawing	38.07	1	4	4	0
Plumbing Fittings	40.02	0	2	19	0
Heating Equipment	40.03	1	1	12	19
Fabricated Structural Steel	40.04	3	2	5	0
Fabricated Plate Work	40.06	1	1	4	0
Sheet Metal Work	40.07	0	1	8	0
Miscellaneous Metal Work	40.09	0	0	6	9
Pumps & Compressors	49.01	1	2	10	0
Blowers & Fans	49.03	0	1	7	0
General Industry Machinery	49.07	0	0	7	0
Industrial Controls	53.05	0	0	5	0

BASIC

Plumbing 40.02 \$59,800

Margins		
Truck	65.03	2%
Wholesale	69.01	19%

$$\text{Truck: } (59800)(.02)(1.296)^{-1}(7739) = .0071419 \times 10^9$$

$$\text{Wholesale: } (59800)(.19)(1.62)^{-1}(6877) = .048232 \times 10^9$$

$$\text{Plumbing: } (59800)(.79)(1.68)^{-1}(28323) = \underline{.79645 \times 10^9}$$

$$.85182 \times 10^9 \text{ BTU CE}$$

Ductwork (HVAC) 40.07 \$80,000

Margins		
Truck	65.03	1%
Wholesale	69.01	8%

$$\text{Truck: } (80000)(.01)(1.296)^{-1}(7739) = .0047772 \times 10^9$$

$$\text{Wholesale: } (80000)(.08)(1.62)^{-1}(6877) = .027168 \times 10^9$$

$$\text{Ductwork: } (80000)(.91)(1.68)^{-1}(57995) = \underline{2.5131 \times 10^9}$$

$$2.545 \times 10^9 \text{ BTU CE}$$

Ductwork (Heat Recovery)
40.07 \$1,000

Margins		
Truck	65.03	1%
Wholesale	69.01	8%

$$\text{Truck: } (1000)(.01)(1.296)^{-1}(7739) = .000059715 \times 10^9$$

$$\text{Wholesale: } (1000)(.08)(1.62)^{-1}(6877) = .0003396 \times 10^9$$

$$\text{Ductwork: } (1000)(.91)(1.68)^{-1}(57995) = \underline{.031414 \times 10^9}$$

$$.031813 \times 10^9 \text{ BTU CE}$$

BASIC (cont'd)

Heat Recovery Equipment 49.07 $1,000

Margins		
Wholesale	69.01	7%

Wholesale: $(1000)(.07)(1.62)^{-1}(6877) = .00029715 \times 10^9$

Heat Recovery Equipment: $(1000)(.93)(1.553)^{-1}(28150) = .016857 \times 10^9$

$.017154 \times 10^9$ BTU CE

Expansion Tanks 40.06 $1,200

Margins		
Rail	65.01	1%
Truck	65.03	1%
Wholesale	69.01	4%

Rail: $(1200)(.01)(1.673)^{-1}(15178) = .00010887 \times 10^9$

Truck: $(1200)(.01)(1.296)^{-1}(7739) = .000071657 \times 10^9$

Wholesale: $(1200)(.04)(1.62)^{-1}(6877) = .00020376 \times 10^9$

Expansion Tanks: $(1200)(.94)(1.68)^{-1}(55202) = .037064 \times 10^9$

$.037448 \times 10^9$ BTU CE

Exhaust/Outside Air Fans 49.03 $1,750

Truck	65.03	1%
Wholesale	69.01	7%

Truck: $(1750)(.01)(1.296)^{-1}(7739) = .0001045 \times 10^9$

Wholesale: $(1750)(.07)(1.62)^{-1}(6877) = .00052002 \times 10^9$

Fans: $(1750)(.92)(1.553)^{-1}(27466) = .028474 \times 10^9$

$.029099 \times 10^9$ BTU CE

BASIC (Cont'd)

Cooling Towers 40.06 \$9,000

Margins

Rail	65.01	1%
Truck	65.03	1%
Wholesale	69.01	4%

Rail: $(9000)(.01)(1.673)^{-1}(15178) = .00081651 \times 10^9$

Truck: $(9000)(.01)(1.296)^{-1}(7739) = .00053743 \times 10^9$

Wholesale: $(9000)(.04)(1.62)^{-1}(6877) = .0015282 \times 10^9$

Cooling Towers: $(9000)(.94)(1.68)^{-1}(55202) = \underline{.27798 \times 10^9}$

$.28086 \times 10^9$ BTU CE

Air Handling Units
49.07 \$35,200

Margins

Wholesale 69.01 7%

Wholesale: $(35200)(.07)(1.62)^{-1}(6877) = .01046 \times 10^9$

Air Handling Units: $(35200)(.93)(1.553)^{-1}(28150) = \underline{.59338 \times 10^9}$

$.60384 \times 10^9$ BTU CE

TOTAL (BASIC) = 4.397×10^9 BTU CE

PREMIUM -- CONVENTIONAL

Water Chillers 49.07 $33,000

Margins

Wholesale 69.01 7%

Wholesale: $(33000)(.07)(1.62)^{-1}\ (6877) = .0098061 \times 10^9$

Water Chillers: $(33000)(.93)(1.553)^{-1}\ (28150) = \underline{.55629 \times 10^9}$

$.5561 \times 10^9$ BTU CE

Heat Exchangers/ Piping 40.06 $35,000

Margins

Rail	65.01	1%
Truck	65.03	1%
Wholesale	69.01	4%

Rail: $(35000)(.01)(1.673)^{-1}(15178) = .0031753 \times 10^9$

Truck: $(35000)(.01)(1.296)^{-1}(7739) = .00209 \times 10^9$

Wholesale: $(35000)(.04)(1.62)^{-1}\ (6877) = .0059431 \times 10^9$

Heat Exchangers/ Piping: $(35000)(.94)(1.68)^{-1}\ (55202) = \underline{1.081 \times 10^9}$

1.0922×10^9 BTU CE

PREMIUM -- CONVENTIONAL (Cont'd)

Heating Equipment 40.03 $3,300

Margins

Rail	65.01	1%
Truck	65.03	1%
Wholesale	69.01	12%
Retail	69.02	19%

Rail:	$(3300)(.01)(1.673)^{-1}(15178)$	=	$.00029938 \times 10^9$
Truck:	$(3300)(.01)(1.296)^{-1}(7739)$	=	$.00019706 \times 10^9$
Wholesale:	$(3300)(.12)(1.62)^{-1}(6877)$	=	$.001681 \times 10^9$
Retail:	$(3300)(.19)(1.527)^{-1}(8627)$	=	$.0035423 \times 10^9$
Heating Equipment:	$(3300)(.67)(1.68)^{-1}(32581)$	=	$.042879 \times 10^9$
			$.048599 \times 10^9$ BTU CE

Pumps 49.01 $1,350

Margins

Rail	65.01	1%
Truck	65.03	2%
Wholesale	69.01	10%

Rail:	$(1350)(.01)(1.673)^{-1}(15178)$	=	$.00012248 \times 10^9$
Truck:	$(1350)(.02)(1.296)^{-1}(7739)$	=	$.00016123 \times 10^9$
Wholesale:	$(1350)(.10)(1.62)^{-1}(6877)$	=	$.00057308 \times 10^9$
Pumps:	$(1350\ (.87)(1.553)^{-1}(24506)$	=	$.018533 \times 10^9$
			$.01939 \times 10^9$ BTU CE

PREMIUM -- CONVENTIONAL (Cont'd)

Controls 53.05 $25,000

Margins

Wholesale 69.01 5%

$$\text{Wholesale: } (25000)(.05)(1.62)^{-1}(6877) = .0053063 \times 10^9$$

$$\text{Controls: } (25000)(.95)(1.367)^{-1}(15875) = .27581 \times 10^9$$

$$.28112 \times 10^9 \text{ BTU CE}$$

Insulation 36.18 $20,000

Margins

Rail	65.01	8%
Wholesale	69.01	5%
Retail	69.02	2%

$$\text{Rail: } (20000)(.08)(1.673)^{-1}(15178) = .014516 \times 10^9$$

$$\text{Wholesale: } (20000)(.05)(1.62)^{-1}(6877) = .0042451 \times 10^9$$

$$\text{Retail: } (20000)(.02)(1.527)^{-1}(8627) = .0022599 \times 10^9$$

$$\text{Insulation: } (20000)(.85)(1.606)^{-1}(25830) = .27342 \times 10^9$$

$$.29444 \times 10^9 \text{ BTU CE}$$

Maintenance & Replacement	12.02	$198,525 14,569 117,439 $330,533	Margins None

$$\text{Maintenance \& Replacement: } (330533)(2.268)^{-1}(14654) = 2.1356 \times 10^9 \text{ BTU CE}$$

TOTAL (PREMIUM--CONVENTIONAL) = 4.427×10^9 BTU CE

PREMIUM -- SOLAR

Solar Co\ $147,050

Compone\

(6%) Glass	35.01	$8,823	Margins			
			Truck	65.03	1%	
			Wholesale	69.01	5%	

Truck: $(8823)(.01)(1.296)^{-1}(7739) = .00052686 \times 10^9$

Wholesale: $(8823)(.05)(1.62)^{-1}(6877) = .0018727 \times 10^9$

Glass: $(8823)(.94)(1.587)^{-1}(23050) = .12046 \times 10^9$

$.12286 \times 10^9$ BTU CE

(6%) Copper	38.07	$8,823	Margins		
			Rail	65.01	1%
			Truck	65.03	4%
			Wholesale	69.01	4%

Rail: $(8823)(.01)(1.673)^{-1}(15178) = .00080045 \times 10^9$

Truck: $(8823)(.04)(1.296)^{-1}(7739) = .0021074 \times 10^9$

Wholesale: $(8823)(.04)(1.62)^{-1}(6877) = .0014982 \times 10^9$

Copper: $(8823)(.91)(1.717)^{-1}(31782) = .14862 \times 10^9$

$.15303 \times 10^9$ BTU CE

PREMIUM -- SOLAR (Cont'd)

Solar Connectors (Cont'd)

(14%) Steel 40.07 $20,587

Margins

Truck	65.03	1%
Wholesale	69.01	8%

Truck: $(20587)(.01)(1.296)^{-1}(7739) = .0012293 \times 10^9$

Wholesale: $(20587)(.08)(1.62)^{-1}(6877) = .0069914 \times 10^9$

Steel: $(20587)(.91)(1.68)^{-1}(57995) = .64672 \times 10^9$

$.65494 \times 10^9$ BTU CE

(2%) Aluminum 40.09 $2,941

Margins

Wholesale	69.01	6%

Wholesale: $(2941)(.06)(1.62)^{-1}(6877) = .00074908 \times 10^9$

Aluminum: $(2941)(.94)(1.68)^{-1}(79388) = .13064 \times 10^9$

$.13139 \times 10^9$ BTU CE

(2%) Insulation 36.18 $2,941

Margins

Rail	65.01	8%
Wholesale	69.01	5%

Rail: $(2941)(.08)(1.673)^{-1}(15178) = .0021345 \times 10^9$

Wholesale: $(2941)(.05)(1.62)^{-1}(6877) = .00062424 \times 10^9$

Insulation: $(2941)(.87)(1.606)^{-1}(25830) = .041152 \times 10^9$

$.043911 \times 10^9$ BTU CE

PREMIUM -- SOLAR (Cont'd)

Solar Collectors (Cont'd)

(15%) Retail Trade 69.02 \$22,058

<u>Margins</u>

None

Retail Trade: $(22058)(1.527)^{-1}(8627) = .12462 \times 10^9$ BTU CE

(55%) New Construction 11.05 \$80,878

<u>Margins</u>

None

New Construction: $(80878)(2.268)^{-1}(26228) = .9353 \times 10^9$ BTU CE

TOTAL Energy for Solar Collectors: 2.1661×10^9 BTU CE

Pumps 49.01 \$3,350

<u>Margins</u>

Rail	65.01	1%
Truck	65.03	2%
Wholesale	69.01	10%

Rail: $(3350)(.01)(1.673)^{-1}(15178) = .00030392 \times 10^9$

Truck: $(3350)(.02)(1.296)^{-1}(7739) = .00040009 \times 10^9$

Wholesale: $(3350)(.10)(1.62)^{-1}(6877) = .0014221 \times 10^9$

Pumps: $(3350)(.87)(1.553)^{-1}(24506) = .045990 \times 10^9$

$.048116 \times 10^9$ BTU CE

PREMIUM -- SOLAR (Cont'd)

Controls 53.05 $35,000

Margins

Wholesale 69.01 5%

$$\text{Wholesale: } (35000)(.05)(1.62)^{-1}(6877) = .0074289 \times 10^9$$

$$\text{Controls: } (35000)(.95)(1.367)^{-1}(15875) = .38613 \times 10^9$$

$$.39356 \times 10^9 \text{ BTU CE}$$

Insulation 36.18 $34,090

Margins

Rail	65.01	8%
Wholesale	69.01	5%
Retail	69.02	2%

$$\text{Rail: } (34090)(.08)(1.673)^{-1}(15178) = .024742 \times 10^9$$

$$\text{Wholesale: } (34090)(.05)(1.62)^{-1}(6877) = .0072357 \times 10^9$$

$$\text{Retail: } (34090)(.02)(1.527)^{-1}(8627) = .0038519 \times 10^9$$

$$\text{Insulation: } (34090)(.85)(1.606)^{-1}(25830) = .46604 \times 10^9$$

$$.50187 \times 10^9 \text{ BTU CE}$$

Maintenance & Replacement 12.02

$427,868
23,819
106,470
$558,157

Margins

None

$$\text{Maintenance \& Replacement: } (558157)(2.268)^{-1}(14654) = 3.6064 \times 10^9 \text{ BTU CE}$$

PREMIUM -- SOLAR (Cont'd)

Collector Supports 40.04 $102,124

Margins		
Rail	65.01	3%
Truck	65.03	2%
Wholesale	69.01	5%

Rail: $(102124)(.03)(1.673)^{-1}(15178) = .027795 \times 10^9$

Truck: $(102124)(.02)(1.296)^{-1}(7739) = .012197 \times 10^9$

Wholesale: $(102124)(.05)(1.62)^{-1}(6877) = .021676 \times 10^9$

Collector Supports: $(102124)(.9)(1.68)^{-1}(69149) = 3.7831 \times 10^9$

3.8448×10^9 BTU CE

Water Chillers 49.01 $61,000

Margins		
Wholesale	69.01	7%

Wholesale: $(61000)(.07)(1.62)^{-1}(6877) = .018126 \times 10^9$

Water Chillers: $(61000)(.93)(1.553)^{-1}(28150) = 1.0283 \times 10^9$

1.0464×10^9 BTU CE

Heat Exchangers/Piping 40.06 $81,455

Margins		
Rail	65.01	1%
Truck	65.03	1%
Wholesale	69.01	4%

Rail: $(81455)(.01)(1.673)^{-1}(15178) = .0073899 \times 10^9$

Truck: $(81455)(.01)(1.296)^{-1}(7739) = .004864 \times 10^9$

Wholesale: $(81455)(.04)(1.62)^{-1}(6877) = .013831 \times 10^9$

Heat Exchangers/Piping: $(81455)(.94)(1.68)^{-1}(55202) = 2.5159 \times 10^9$

2.542×10^9 BTU CE

PREMIUM -- SOLAR (Cont'd)

Heading Equipment 40.03 $7,800

Margins

Rail	65.01	1%
Truck	65.03	1%
Wholesale	69.01	12%
Retail	69.02	19%

Rail: $(7800)(.01)(1.673)^{-1}(15178) = .00070764 \times 10^9$

Truck: $(7800)(.01)(1.296)^{-1}(7739) = .00046577 \times 10^9$

Wholesale: $(7800)(.12)(1.62)^{-1}(6877) = .0039734 \times 10^9$

Retail: $(7800)(.19)(1.527)^{-1}(8627) = .0083728 \times 10^9$

Heating Equipment: $(7800)(.67)(1.68)^{-1}(32581) = .10135 \times 10^9$

$.11487 \times 10^9$ BTU CE

Total (Premium -- Solar) $= 14.264 \times 10^9$ BTU CE

Annual Equipment Energy Values for Each HVAC System:

Total (Conventional) =

$$\frac{(4.397 + 4.427) \times 10^9}{35 \text{ years}} = 2.524 \times 10^8 \text{ BTU CE/year}$$

Total (Solar) =

$$\frac{(4.397 + 14.264) \times 10^9}{35 \text{ years}} = 5.3 \times 10^8 \text{ BTU CE/year}$$

APPENDIX E

SOLAR COLLECTOR COMPONENT COST

Appendix E

SOLAR COLLECTOR COMPONENT COST

Since solar collectors are not a typical product of our economy, a process analysis is necessary to determine its energy cost. The flat plate, double glazed solar collector used in the BX project, marketed by Raypak, Inc., was broken down into five major components: plate glass, copper tubing, steel casing, aluminum absorber plate, and insulation. Raypak was contacted in an effort to determine what percentage of the total collector cost ($400.00) was devoted to each of the five components mentioned above. Unfortunately, Raypak declined to reveal this information to the researchers, who were then forced to contact local (Dayton area) manufacturers/distributors of the components. The following listing provides approximate costs (medians of several quotes) for the five collector components:

Glass:	$.72 per square foot
Copper:	$.40 per foot for 3/8 inch tubing $.64 per foot for 3/4 inch tubing
Steel:	$55.00
Aluminum:	$6.60
Insulation:	$.55 per square foot

The cost data above, include considerations for volume purchasing, which in this case is enough of each material for about 700 of the 34 by 76 inch collectors (12,500 ft^2 total area). The cost of the glass, copper, steel, aluminum, and fiberglass insulation in each collector is displayed below:

Glass:	($.72/$ft^2$)(2)(34 in)(76 in)/ (144 in^2/ft^2)	= $ 25.84
Copper:	3/8 inch tubing; ($.40/ft)(9) (70 in)(1 ft/12 in)	= 21.00
	3/4 inch tubing; ($.64/ft)(2) (1 ft/12 in)	= 3.20
Steel:	34" x 76" x 2" casing	= 55.00
Aluminum:	34" x 76" absorber plate	= 6.60
Insulation:	($.55/$ft^2$)(34 in)(76 in)/(144 in^2/ft^2)	= 9.87
		$121.51

The percentage of the total collector cost attributed to each component is as follows:

Glass:	$25.84/$400.00	= 6%
Copper:	($21.00 + $3.20)/$400.00	= 6%
Steel:	$55.00/$400.00	= 14%
Aluminum:	$6.60/$400.00	= 2%
Insulation:	$9.87/$400.00	= 2%
		30%

The remaining 70% of the collector cost is contained in the labor required to assemble the collector and the retail mark-up. The researchers will assume the percentages of total collector cost attributable to labor and retail mark-up to be 55% and 15%, respectively.

APPENDIX F

ENERGY BALANCE CALCULATIONS
FOR THE HVAC SYSTEMS

Appendix F

ENERGY BALANCE CALCULATIONS FOR THE HVAC SYSTEMS

CONVENTIONAL SYSTEM

Air Conditioning Load

214264 ton/hr taken from Preliminary Design Report (see Table 9) converted to BTUs:

$$214264 \text{ ton/hr} \times 12{,}000 \frac{\text{BTU/hr}}{\text{ton}} = 2.57 \times 10^{9} \text{ BTU}$$

The output is in terms of BTUs. Next, the 2.57×10^{9} BTU were converted to electrical power equivalents. To do this, it was assumed that the air conditioning system, when operating at 100% efficiency, would have a coefficient of performance (COP) of approximately 5.0.

$$2.57 \times 10^{9} \div 5.0 = 5.14 \times 10^{8}$$

Thus the associated outputs and losses in the air conditioning system follow:

$$\begin{array}{ccccc} \text{INPUT} & = & \text{OUTPUT} & + & \text{LOSSES} \\ 6.77 \times 10^{8} & = & 4.14 \times 10^{8} & + & 1.63 \times 10^{8} \end{array}$$

The input is taken from the Preliminary Design Report (see Table 9). This input is the electrical power supplied to the chiller.

These values were then converted to BTU coal equivalents (CEs) using the factor 2.0198 taken from the Bullard report (3:46).

Electric Chiller Input:	$6.77 \times 10^8 \times 2.0198 = 1.367 \times 10^9$ CE
Cooling Output:	$5.14 \times 10^8 \times 2.0198 = 1.038 \times 10^9$ CE
Losses:	$1.63 \times 10^8 \times 2.0198 = 3.292 \times 10^8$ CE

Space Heating Load

385411000 BTU taken from Preliminary Design Report (see Table 9). The output was converted to coal equivalents using the factor .0112 taken from the Bullard report (3:46).

$$385411 \times 10^3 \times .0112 = 4.3166 \times 10^6 \text{ CE}$$

Domestic Hot Water (DHW) Demand

134564×10^3 BTUs was taken from the Preliminary Design Report (see Table 9). The output was converted to coal equivalents using the factor .0112 taken from the Bullard report.

$$134564 \times 10^3 \times .0112 = 1.5071 \times 10^6 \text{ CE}$$

To calculate the losses from the space heating and DHW processes, the space heating and DHW outputs were added:

$$4.3166 \times 10^6 \text{ CE} + 1.5071 \times 10^6 \text{ CE} = 5.8237 \times 10^6 \text{ CE}$$

Since natural gas is used only for these two processes, the yearly natural gas input (see Table 9) was converted to coal equivalents using the factor .0012.

$$6.933 \times 10^{8} \text{ BTU} \times .0112 = 7.765 \times 10^{6} \text{ CE}$$

The researchers assumed that the gross losses incurred in both processes could be determined by subtracting the outputs from the inputs.

INPUTS	-	OUTPUTS	=	LOSSES
7.765×10^{6} CE	-	5.8237×10^{6} CE	=	1.9413×10^{6} CE

The gross efficiency of the processes is:

$$\frac{5.8237 \times 10^{6}}{7.765 \times 10^{6}} = .7499$$

Therefore the approximate overall efficiency is 75% which is close to the accepted efficiency of burning natural gas (i.e. 80%). It was assumed that the additional 5% loss is due to storage tank and distribution losses. The following are the associated losses for the processes.

	OUTPUT	+	LOSS	=	TOTAL
Space Heating (74%):	4.3166×10^{6} CE	+	1.437×10^{6} CE	=	5.7536×10^{6} CE
DHW:	1.507×10^{6} CE	+	5.0474×10^{5} CE	=	$\underline{2.01184 \times 10^{6}}$ CE
			TOTAL	=	7.755×10^{6} CE

Next, the researchers looked at the inputs to the conventional system, taken from Table 9, and converted these yearly values to CEs.

Natural Gas: 6.933×10^8 BTU x .0112 = 7.765×10^6 CE

Electricity: 531827 KWH x 3413 BTU/KWH x 2.0198 = 3.662×10^9 CE

There is one large difference between the electric input and the electric input to the air conditioner chiller unit. This difference is associated with the auxiliary power needed to operate the total HVAC system (i.e., pumps, controls, recovery fans, etc.).

Aux. Electric = Yearly Electric - Chiller Input

Aux. Electric = 3.67×10^9 CE - 1.367×10^9 CE

Aux. Electric = 2.303×10^9 CE

SOLAR SYSTEM

The first assumption was that the outputs are the same for each system.

Outputs:

Cooling	1.038×10^9 CE
Space Heating	4.316×10^9 CE
DHW	1.507×10^9 CE

Because of the integrated system, the data available did not differentiate between the different processes. Therefore,

the losses involved in the processes had to be determined as aggregated values.

The main assumption in the solar system is that the solar contribution to the cooling process was insignificant, and the solar contribution to the space heating and DHW was approximately 100%.

To calculate the losses incurred in the solar process, the small contribution of DHW, in the form of natural gas, was subtracted from the sum of the outputs.

Space Heating +	DHW	- Natural Gas Contribution	
4.3166×10^6 +	1.5071×10^6	$- 5.954 \times 10^4$	$= 5.76416 \times 10^6$ CE

This value is the amount of energy needed from the solar storage tanks. Assuming a 10% tank loss, the input to the storage tank is:

OUTPUT	+	10% LOSS	=	INPUT
5.764×10^6	+	$.5764 \times 10^6$ CE	=	6.34×10^6 CE

The thermal efficiency of the solar system is assumed to be 65% taken from the report by Brown and Zucchetto (2).

65% OUTPUT + 35% LOSS	=	TOTAL SOLAR INPUT
$6.34 \times 10^6 + 3.414 \times 10^6$	=	9.754×10^6 CE

The calculated, balanced energy flows for both HVAC systems are presented in Table 22.

TABLE 22

BALANCED ENERGY FLOWS FOR EACH SYSTEM

(BTU CE)

	Conventional	Solar
Inputs		
Equipment	2.524×10^8	5.3×10^8
Natural Gas	7.765×10^6	7.94×10^4
Electricity	3.67×10^9	4.6×10^9
Solar	- 0 -	9.75×10^6
Outputs		
Cooling	1.038×10^9	1.038×10^9
Heating	4.317×10^6	4.317×10^6
DHW	1.507×10^6	1.507×10^6
Losses		
Cooling	3.29×10^8	3.566×10^9
Auxiliary Electric	2.632×10^9	
Heating	1.44×10^6	3.41×10^6
DHW	$.503 \times 10^6$	
Solar Storage Tank	- 0 -	$.58 \times 10^6$

The amount of water necessary for the DHW process can be determined from the equation below:

$$\text{DHW Output} = mc\,\Delta T$$

where m is the amount of water required (gallons), c is the specific heat of water, 1 $^{BTU}/_{lb\text{-}°F}$, and ΔT is average difference between the input (60°F) and output (140°F) water temperature (17). Thus, the amount of water required is:

$$\text{Water Requirement} = \frac{134564 \times 10^3 \text{ BTU}}{(1\ ^{BTU}/_{lb\text{-}°F})(140\text{-}60°F)(8.34\ ^{lb}/_{gal})}$$

$$= 2.02 \times 10^5 \text{ gallons}$$

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